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APPLICATIONS OF SYSTEMS ANALYSIS MODELS

A SURVEY

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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Foreword

The size and complexity of the challenges met by the National Aeronautics and Space Administration have necessitated the use of mathematical management models and systems analysis. Similar models and methods can be used in the management of many other large-scale or complex efforts, in both the private and the public sectors of the economy.

The Office of Technology Utilization strives to enable both industry and other government agencies to benefit from NASA's experience and findings. It does this in part by reporting them in appropriate ways. This is one of a series of special publications issued for this purpose. Most of them have been addressed to specialists in narrower fields. This one deals with concepts and developments applicable to a broad spectrum of human problems.

This publication discusses the adaptation and application of know-how and methods that NASA has used to problems that continually confront management, for example, long-range planning, cost effectiveness and control, and market development. It also deals with the use of these modern techniques in urban and regional planning, and points out their potential helpfulness to city officials and the administrators of public health, educational, and other programs. It emphasizes NASA-funded work that may be as meaningful outside the aerospace field as it has been within it.

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CHAPTER I

Introduction

A GENERAL DESCRIPTION OF MATHEMATICAL MANAGEMENT MODELS AND SYSTEMS ANALYSIS TECHNOLOGY

The last several decades have witnessed the growth of a much-heralded new approach to management problems, the "systems analysis" approach. Systems analysis technology is a rather loosely defined spectrum of techniques related to each other by several common characteristics which describe the approach taken to problem solving—specifically, a systematic and usually quantitative approach which concentrates on the system as a whole, as opposed to its constituent elements. The techniques which comprise this new technology are labeled in a variety of ways: operations research, operations analysis, cost-benefit analysis, engineering-economic analysis, etc. This survey report will be largely unconcerned with drawing any distinction between these categories, for such distinctions are artificial at best. Rather, the report will simply refer to the whole field as the technology of mathematical management models or systems analysis, and proceed to focus on the application of the entire family of techniques.

What areas of knowledge are opened by this new technology? What new problems can be solved? The answer is "none," in at least one fundamental sense. An appreciation of this somewhat blunt fact is necessary to understand the role of the systems approach properly. True, the combination of the digital computer and new analytical techniques can provide a spectacularly more efficient way of solving problems. In this sense, then, the new technologies do allow the solution of new problems because of the great time and cost savings inherent in their efficiency. But the real value of systems techniques resides in their systematic and efficient approach to problem solving, not in the addition of new theoretical concepts to a field of knowledge.

Frequently, decisionmakers newly introduced to management models and systems techniques can be heard decrying their effectiveness: "But they don't really solve my most troublesome problems." Indeed models often do not; nor should they always be expected to do so. No matter what the field of application, there are very basic substantive questions which cannot be circumvented by the use of systems technology. These techniques provide a conceptual framework for dealing with problems, a systematic and efficient approach to problem solving, but no new magical answers for many questions. The potential utility of these techniques must be understood in these terms.

THE USE OF SYSTEMS TECHNOLOGY IN NASA-SPONSORED PROJECTS

One of the most fruitful areas for the application of systems techniques has been the aerospace industry. The association of systems technology with the aerospace industry in general and NASA-sponsored projects in particular should not be surprising. First of all, the management personnel administering NASA-supported projects have often been familiar with the use of quantitative techniques because of their previous education and experience. Second, the management tasks required by these projects often have been susceptible to quantitative and systematic approaches. Finally, the projects themselves have been so large and complex that systems techniques were not only desirable but also necessary for adequate management. Thus, for all these reasons, systems management techniques have often been developed for and specifically tailored to various NASA-supported aerospace projects.

THE POTENTIAL FOR USE IN NONAEROSPACE ENDEAVORS

Can systems techniques be altered and transferred to nonaerospace endeavors? Once transferred, will these techniques really aid problem solving in nonaerospace endeavors? The thesis of this survey report is that such transfers are not only possible but potentially beneficial. Recall that the common characteristics of systems technology focus on the type of approach to problem solving, not on the specific class of problems involved. These management models can be used to attack large classes of problems in many disparate areas. It is also possible to locate specific techniques developed for NASA projects which can be used for large classes of problems.

AN OVERVIEW OF THE REPORT

This survey report has been divided into three general sections. The general problems which arise in transferring management models and systems techniques will be discussed in chapter II. These problems are mirrored in the organization of the remainder of this document. Because of the nature of the subject matter, the transfer of systems analysis technology is a very different process than the transfer of any hardware-specific technology. Whereas the potential for transferring a hardware-specific technology lies within the context of a set of particular technical disciplines, the potential for transferring systems analysis spans the entire breadth of complex systems in both the private and public sectors of our economy. This document was prepared for readers whose interests span the entire breadth of possible areas of application, yet who as individuals are interested in only some smaller spectrum of problems. Others have attempted to reach this wide audience by very general and abstract discussions of the merits of systems analysis, without reference to specific techniques and problem areas. While some general and abstract discussions are worthwhile, much is lost by not focusing on the specific possibilities for technology transfer both in terms of techniques and problem areas. This survey will follow a middle course between the demands for wide coverage and specific discussions of techniques.

Chapter III is addressed to readers who have had only limited experience with systems analysis. This chapter attempts to span the entire spectrum of possible application areas in both the public and private sectors of the economy. Potential problem areas are discussed, and the applicable system techniques are described in general terms. Chapter IV then delves into each of these techniques in greater detail and references the appropriate source documents. In a sense, then, chapters III and IV form an interrelated matrix of application areas and techniques; chapter III covers the wide spectrum of application areas, and chapter IV concentrates on particular techniques which might be applied in several of these problem areas. The interested reader may find it helpful to refer back and forth between these chapters when considering the prospects for application in his particular problem area.

CHAPTER II

General Problems Involved in the Transfer of Systems Analysis Technology

THE NATURE OF NASA-SPONSORED PROJECTS AND THEIR MANAGEMENT TASKS

The exploration of outer space has added a new technology to man's store of knowledge and a new perspective to his view of the environment. The spacecraft which set out upon long journeys are complex structures, combining a myriad of subsystems and components. They are produced by a complex system of men and machines; of contractors and subcontractors; of research, development, and flight operations. Space programs are typically multiobjective programs, with overlapping and mutually reinforcing hierarchies of objectives. Furthermore, these objectives are extremely difficult to quantify in terms of some convenient scale of value. What is the "value" of scientific knowledge about the Martian atmosphere, the Martian surface, or the lunar surface? Agreement on even a relative scale of preferences for those objectives, much less a more absolute scale related to monetary cost, is difficult, and planning and administering space projects is a complex multidimensional system of problems.

Several types of management problems can be discerned from the general background of administrative tasks. There is a crucial need for long-range planning because space projects must be initiated years in advance of the launch dates. The long-range objectives of our space programs must be congruent with, if not derived from, the goals of the nation as a whole. Because different space projects overlap and mutually support one another, there must be a master system for coordinating timing, resources, and scientific objectives. The cost and personnel requirements of projects must be accurately estimated many years in advance. The availability of funds must be ensured insofar as possible, and the necessary personnel must be educated and trained. These tasks amount to the specification of an overall longrun strategy of space exploration, which properly coordinates each of the individual space projects.

Once a commitment is made to design, develop, and build a spacecraft for a particular mission, a second set of management problems is encountered. From the initial design phase until the completion of the project, the spacecraft and its management team must operate within stringent limits on weight, performance, and schedule. This must all be accomplished subject to certain cost constraints. The design and development phase of the project requires a host of trade-offs between conflicting criteria of performance, schedule, and costs, and the effects on different contractors and subcontractors must be considered. The management framework must be designed to accomplish these trade-offs in an efficient and, hopefully, systematic way.

Finally, once the spacecraft is developed and tested, the actual mission operations begin. This operational phase introduces a third set of management problems, where the emphasis is on quick, efficient data handling and decisionmaking. Strict schedules are mandatory, and the utmost reliability of in-flight operational procedures is necessary.

The above management problems, ranging from long-range planning to in-flight operations, encompass and classify the range of administrative tasks facing NASA and its contractors. In view of the size and complexity of these tasks, it is not surprising that systems management techniques have been developed and utilized. However, these tasks are not limited to the aerospace industry; they are constantly recurring problems in many types of nonaerospace endeavors, and may be typical for large-scale, project-oriented activities.

A DESCRIPTION OF SIMILAR MANAGEMENT TASKS OUTSIDE THE AEROSPACE INDUSTRY

Similar management tasks occur frequently in both nonaerospace industry and urban or social programs. The same three general phases of problems, i.e., long-range planning, the development of specific projects, and operational procedures, can be discerned in the management tasks surrounding almost any activity. If the scale of program or enterprise is small enough in some relative sense, most or all of these tasks can be handled on an "intuitive" basis, without resorting to systems analysis techniques. A certain "critical mass" in terms of both problem size and complexity is required before systems techniques can be effectively employed. Below this threshold, the costs of developing systems approaches often outweigh the potential advantages. Above this threshold, though, the benefits accruing from a systematic and efficient problem-solving approach are well worth the effort. The managers of both large industrial enterprises and large urban or social programs should thus consider the use of systems techniques in attacking broad classes of management problems.

Management Tasks in Large Corporations

A quick glance at the problems of large business corporations reveals many interesting similarities to aerospace projects. The organizational structure of large corporations with a profit center system resembles the contractual hierarchy of contractors and subcontractors in a space program. The general management tasks can be divided in an analogous manner into long-range planning, project (or process) development, and operational procedures. There are similar needs for cost estimation and control, personnel planning and training, and overall resource allocation. Although the general structure and problem-solving orientation are similar, important differences influence the applicability of systems techniques.

First of all, long-range planning must somehow include the impact of a competitive environment. The uncertainty introduced by this competitive environment adds another dimension to the problems of long-range planning. This considerably complicates the decisionmaking process. In this sense, it may be more difficult to employ systems analysis techniques in long-range planning for corporate strategy than in NASA projects.

There is another sense, however, in which it may be easier to apply systems techniques in corporate business. Long-range corporate objectives can be more easily identified with a single goal, namely the maximization of longrun profits. Furthermore, this longrun objective is already quantified in terms of a most convenient numéraire, dollars. The existence of this single, readily quantified, objective removes many of the potential ambiguities surrounding the use of systems techniques. Long-range planning for corporate enterprises can thus be either more or less susceptible to systems techniques, depending on the character of the problem to be solved.

The two later phases, the project (or process) development phase and the operational phase, represent the real core of corporate activities. In NASA work, the preponderance of funds and personnel are involved in the project design and development phase, and the mission operations phase accounts for a relatively small allocation of the total resources. This emphasis is usually reversed in corporate business, where the majority of allocated resources is devoted to current operations. Despite this reversal of emphasis, similar problems of management control appear in private industry, thus inviting the transfer of systems techniques.

Urban and Social Programs

There is often an even closer analogy between the management tasks of urban and social programs and NASA programs. Both are usually conducted on the same type of program or project basis, where the objectives of different projects overlap and hopefully are mutually supporting. Urban or social programs are usually multiobjective programs, encompassing a whole range of socioeconomic goals. Finally, these objectives are usually difficult to quantify in terms of either their absolute or relative importance.

Similar types of management tasks are required as these programs progress. Long-range planning is a crucial element in the overall management of urban and social programs. The estimation of both funding and personnel requirements is essential to effective planning. The design of particular programs involves many of the same trade-offs of cost, schedule, and performance, though performance must be measured by very different criteria. Finally, the operational phase requires some data-handling and scheduling capability, although the emphasis on speed in these operations may not be as crucial as it is in space missions. In perspective, then, the general structure of urban and social program management tasks is similar to that of problems in an aerospace program.

THE PROCESS OF NATURAL TECHNOLOGY DIFFUSION AND NONDIRECT TRANSFER

If we agree that the management tasks of the aerospace projects are similar to many problems which occur outside the aerospace industry, then we must reasonably expect the transfer of systems technology. Undoubtedly the largest and most important part of this transfer flow will occur through the natural and nondirect diffusion of technology. NASA-supported projects have obviously contributed to the recent growth in the general body of knowledge and level of expertise surrounding systems management. This overall expertise is diffusing, and will continue to diffuse, through many related areas. Typical channels through which this diffusion occurs are universities, nonprofit institutions, and diversified corporations operating partially in the aerospace field. Furthermore, the space program is developing a large body of experts trained in the methods of systems analysis. As these highly skilled people venture into other areas of endeavor, they will naturally bring their skills in systems techniques to bear on new and different problems.

These channels for natural diffusion may be the most important media for eventual utilization of systems techniques outside the aerospace industry. Because of the indirect character of the diffusion process, though, it is a difficult phenomenon to document with any concrete detail. This survey will not deal in any depth with this natural but indirect technology transfer, except to note its great importance. It will emphasize rather the potential for more direct transfer of specific systems analysis techniques.

THE PROSPECTS FOR MORE DIRECT TRANSFER OF SYSTEMS ANALYSIS TECHNIQUES

Before proposing more direct technology utilization, it is instructive to consider the nature of a management system and its relation to technology. A management system, be it for an aerospace project, a corporate enterprise, or an urban and social program, must be a structure specifically tailored to the nature of the problem areas within which it will operate. There are no general formulas of structures which are universally applicable to systems management problems. It is useless to speak of transferring mathematical management systems in the sense of lifting complete management systems from one problem context and applying them completely to another. The possibilities for application are, of necessity, much less all-inclusive opportunities. A management system is a collection of techniques "packaged" into an overall unit adapted for problem solving. It is these individual techniques, referred to as systems analysis techniques or models, which may be transferred to new and different endeavors. The elements of a potential management model which is to be transferred must be suitably altered, and recombined into an overall problem-solving approach in the new problem context. Only then will the application process be successful. This latter type of transfer process, where the emphasis is on the alteration and transfer of techniques, will be the subject of this report.

CHAPTER III

Potential Areas of Application of Systems Analysis Concepts

THE APPLICATION OF SYSTEMS TECHNIQUES FOR BUSINESS CORPORATIONS OUTSIDE THE AEROSPACE INDUSTRY

Systems Concepts for Corporate Long-Range Planning

Accompanying the recent growth of scientific approaches to management, there has been a growing concern with the problems of long-range planning. Unfortunately, long-range planning is a function of business administration in which it is difficult to employ quantitative systems techniques successfully. By definition, this planning must deal with the environment and the problems of the future, often the remote future. As the time scale becomes more remote, the uncertainty usually increases at an alarming rate, until quantitative techniques must be used with some skepticism. The host of factors inherent in a competitive environment are particularly difficult to estimate or predict. But these factors are so crucial to the operation of many firms that the accuracy and precision of the long-range planning function are called to question. In many situations, even fairly sophisticated probabilistic tools sometimes can be of very dubious value. Because long-range planning is such a crucial function, however, administrators must search for adequate systems techniques in the face of these known limitations. This section of the report will describe the salient tasks involved in long-range planning, and suggest systems techniques which may be helpful in each of these task areas.

What functions are integral and necessary parts of the long-range planning process? Any attempt to describe these functions runs a substantial risk of being little more than an artificial categorization of a continuous thought process. At the risk of this indictment, however, the following list is offered as an example of the necessary steps in an effective long-range planning program:

(1) The assessment of corporate strengths and weaknesses; the assessment of available and potential resources

(2) The assessment of relevant environmental factors, including economic, sociological, technical, and competitive factors; the location of future opportunities

(3) The formulation of clear objectives and general corporate strategy

(4) The formulation of specific programs pursuant to these objectives and strategy

(5) The evaluation of specific programs according to their effectiveness and the resources consumed

(6) The recommendation of alternative strategies and programs

The long-range planner must continually consider all of these matters, and the sequential ordering, while logically consistent, may not be of great importance. This list, however, encompasses the major problem areas. With proper adaptation, systems analysis techniques can be a valuable aid in several of these areas.

The general assessment of corporate strengths and weaknesses is primarily a qualitative task. In this area, quantitative techniques can perform only limited assignments, such as the projection of available resources of a particular nature. The projection of anticipated cash flows from planned projects, for example, is a limited but important task. Systems techniques can be effectively used to analyze and project these cash flows. In addition, quantitative techniques can be utilized to project the availability of scarce resources such as personnel. The techniques for long-range probabilistic planning developed under NASA funding (see Probabilistic Long-Range Planning in ch. IV) might be particularly helpful in this regard. In general, the output of resource projections provide useful data for the assessment of corporate strengths and weaknesses.

The second step in the long-range planning process, the assessment of all relevant environmental factors, is a difficult and complex task. There are several ways in which quantitative techniques can be useful in this area. First, any environmental situation usually contains several pertinent parameters for which quantitative data can be obtained. This is particularly true for parameters related to the economic situation, though data often can be obtained for other factors as well. Forecasting techniques can be profitably employed to furnish estimates of the future values of these parameters. Of course, there are many methods of forecasting, any of which may be appropriate in a given situation.

A particularly systematic and sophisticated approach to the general forecasting problem forms the heart of the FAME (Forecasts and Appraisals for Management Evaluation) system, a management system developed by NASA for use on the Apollo project (see FAME—An Information and Control System Developed for the Apollo Program in ch. IV). One or several of the forecasting techniques used in that system may be suitable for use in projecting relevant factors in the corporate environment. For many corporations, an assessment of the actual environment becomes very difficult because of the competitive nature of the markets in which they operate. The elements of game theory have been used in an attempt to analyze these problems. They provide a method for assessing opportunities and developing strategies in a competitive environment. The combination of probabilistic forecasting techniques and game theory can be an effective tool to deal with the exigencies of a highly competitive environment.

Once corporate resources and environmental factors have been assessed, objectives can be established and programs formulated. The basic task is to design and formulate a program that is optimal in some "sense" related to the corporate objectives which have been established. Many optimization methods, often referred to as "programing" methods, have been developed in recent years. Linear programing, integer programing, and dynamic programing are examples of these techniques. Depending on the particular problems which are encountered, a number of these techniques might be profitably employed. If all the corporate objectives are not readily defined in terms of a convenient numéraire such as profit, some preconditioning of the optimization problem may be necessary; that is, the other objectives must be included somehow in a performance criterion susceptible to analysis and measurement. An example of the derivation of such a performance criterion is included in Mission Success Evaluation—A Technique for Deriving and Utilizing Measures of Performance in chapter IV. This kind of analysis can often be a helpful precursor to the actual design and optimization of a program.

Once a program has been formulated, it must be evaluated with respect to all the relevant performance criteria. There are many disparate ways to perform this evaluation, depending on the particular problem situation. One important method of evaluation is the use of simulations. Simulations generally involve the use of mathematical models to represent an actual functioning system. An excellent example of simulation techniques was developed to evaluate the operations of manned space stations (see Mathematical Simulation of a Manned Space Mission in ch. IV). Similar techniques could be used to simulate the operations of any large complex undertaking. The complete program evaluation must also include an estimation of costs. Cost-estimation techniques developed with NASA funding might be adapted for use in computing costs for large corporate programs. Several of these cost-estimation techniques are described in detail in The Manned Spacecraft Cost Model in chapter IV. Though the particular cost-estimating relationships must be carefully adapted to the problem situation at hand, the overall costing system framework is a useful and potentially transferable technique. It may also be necessary to project scarce resources (other than monetary cost) which will be consumed by a program or combination of programs. This can be difficult, particularly when uncertainties surround these programs. In many firms, for example, it is necessary to construct long-range manpower plans for highly skilled personnel. But these programs may be dependent upon uncertain events, such as the successful bidding on a given set of contract proposals. And even if the eventual completion of a program can be deemed certain, its starting date and schedule may be highly uncertain. In these situations, a system of long-range probabilistic planning can be desirable or necessary. Such a system has been developed under NASA funding (see Probabilistic Long-Range Planning in ch. IV) for use in project-oriented aerospace activities. It is equally applicable in nonaerospace activities, and may form the nucleus of an industrial system for evaluating program costs and personnel requirements. Furthermore, this system could be easily adapted to help estimate program requirements for other scarce resources including plant and equipment. Thus, although the evaluation of proposed programs must be individually tailored, there seem to be at least three potentially useful general techniques that have been developed with NASA funding:

(1) Comprehensive simulation techniques
(2) Systematic cost-estimating techniques
(3) Long-range probabilistic planning techniques

The adaptation of one or several of these kinds of techniques can be very helpful for long-range program evaluation.

As an example of the application of long-range probabilistic planning techniques, consider a corporation attempting to project future requirements for scarce resources over the next several years. Assume that this corporation has a number of potential new products currently in the development phase. The company is uncertain whether several crucial development problems can be solved. Even if the corporate management is confident of a successful development phase, it may not be certain how long this product development will take. Furthermore, the uncertainties of the competitive environment make it difficult to estimate the potential demand for the product once it is marketed. In the midst of these uncertainties, how can the corporation estimate its future resource requirements? How can it estimate the personnel and costs required to manufacture unproven products for an uncertain market at some uncertain time? The techniques of "probabilistic long-range planning" can be used here as an effective framework to structure the long-range planning problem.

First of all, each potential new product must be isolated and characterized by the resources required for its manufacture and marketing. These resources may include particular types of manpower, direct marketing costs, equipment, plant space, and the like.

The subsequent steps then could be as follows: Divide the time starting from a hypothetical product introduction date into equal, regularly spaced periods. For each product, estimate the resource requirements as a function of time, starting from this hypothetical market introduction time. This calculation should make use of the concept of product life cycle and the variance of resource requirements over the life cycle. Then structure this information into a matrix where the rows are the different resource categories and the columns are the time periods measured from the product introduction time. For each product, there will be a representative matrix where the ij element (the number in the i^{th} row and the j^{th} column) is the amount of the i^{th} resource required during the j^{th} time period after introduction. At this point, the long-range planners must construct subjective probability distributions for the introduction time of all products in terms of real time. With these probability distributions, a master matrix can be formed which represents the total expected resource requirements as a function of time. To obtain this matrix, multiply all the matrices for individual products by the subjectively derived probability that they will be introduced into the market in the k^{th} time period, and add them to the master matrix so that column "l" of each individual matrix corresponds to the k^{th} column of the master matrix. When this is done for all time periods, the total values of the master matrix represent total expected resource requirements in real time. Once this master matrix is formed, many useful calculations can be derived for long-range planning purposes by using simple matrix manipulation routines.

These calculations could be simply performed by a computer. For example, given the rows corresponding to various categories of needed personnel, subtract the j^{th} column from the $(j - l)^{th}$ column to estimate the hiring that will be required in the j^{th} period. Similarly, the amount of new equipment that must be purchased and the new plant space that must be bought or leased in the j^{th} period can be estimated. The costs of hiring different types of personnel can be represented by a vector. The product of this vector with the vector representing hiring needs in the j^{th} period is the total cost of hiring in the j^{th} period. Similarly, the total costs of acquiring new equipment and leasing new space in the j^{th} period can be computed. All these costs can be accumulated and added to the direct monetary costs (e.g., working capital required) to yield estimates of total costs as a function of time. Various other relevant calculations can be made to aid in the long-range planning process. These calculations are described in reports compiled in reference 1.

When alternative programs have been evaluated, the most desirable program or combination of programs must be recommended to complete the long-range planning function. This requires a decision, often among mutually exclusive sets of programs. Recently, a branch of management science known as statistical decision theory has evolved to aid in this decision process. Several techniques encompassed by decision theory have already been used, with varying success, by several large corporations. One of the largest and most comprehensive examples was the application of decision-theory techniques in the NASA Voyager project. The methods employed in this study can be adapted for use by many large corporations. The use of these decision techniques is really an attempt to augment the more intuitive, but often less reliable, judgment of managers. This judgment can never be replaced, but recent studies have shown that it can clearly be improved by using these quantitative methods. The techniques are described in detail in Application of Decision Analysis to Complex Program Strategies in chapter IV.

In summary, although the long-range planning task must contend with uncertainties which are difficult to quantify, systems techniques are nevertheless desirable, useful adjuncts to the intuition of decisionmakers. The long-range planning department of any large corporation might profitably consider the use of the following analytic techniques:

(1) Systematic forecasting tools
(2) Game-theory techniques
(3) Optimization methods such as "programing" techniques
(4) Simulation systems
(5) Comprehensive cost-estimating systems
(6) Probabilistic long-range planning techniques
(7) Statistical decision-theory techniques

For corporations which have not yet mastered the use of these techniques, NASA programs can serve as helpful examples of their potential use. Other sections of this report describe the manner in which these techniques were used in NASA programs, and more complete documentation can be found in the bibliography and the current management science literature.

The Optimization of Complex Production Systems

The design or modification of a large production system is often envisaged as a single-stage process which is completed at some definite point in time. Most theories of production design attempt to develop an "optimal" system design, in which optimality is implicitly defined with respect to that point in time. In reality, however, the design and modification of a production system is a constantly recurring sequence of acts, each of which results in some alteration of the existing facilities. In this sense, the design function should be considered a continuous dynamic process instead of a single-stage decision problem. In order to plan the design function properly, this new time dimension should be introduced into the analysis.

Statistical decision-theory techniques are an excellent vehicle for including this crucial element of time. These techniques allow the systems analyst to consider and to formulate the design process as a multistage decision problem. The objective of an appropriate design policy is to formulate strategies which provide for the *evolution* of an optimal system design. This important shift in emphasis from "optimality at the present time" to an "evolution toward optimality" can have important consequences for corporate strategy. It is, first of all, a more realistic structuring of the design problem. Second, it recognizes that all design decisions cannot and should not be made immediately. Third, it provides a structure for ordering the important design decisions so that they make maximal use of the intervening time periods.

Statistical decision theory is not a substitute for previously developed operations research techniques. Decision theory is, instead, a general framework into which these other techniques can be incorporated. The phrase "optimal design" has had a hollow ring because the existing techniques have defined optimality without regard to the institutional and corporate constraints which impinge upon the design process. By including these "optimizing techniques" in an overall strategy, which takes into account, as well as advantage of, timelags, optimality can be made a more meaningful concept. Application of Decision Analysis to Complex Program Strategies in chapter IV describes the methodology in statistical decision theory as applied to strategies for designing and controlling a large space program. This same type of analysis can be adapted to design problems for complex manufacturing processes.

As the production process becomes more complex, the ability of operations analysts to solve systems problems becomes more limited. Many large manufacturing processes have become so complex that it is not practical to solve production problems with closed form analytical techniques. This is particularly true for manpower intensive processes where the human elements introduce uncertainties into an already formidable problem. In such problematic situations, the use of simulation techniques holds real promise for a practical systems approach. NASA has utilized simulation techniques to design and schedule complex space missions. Mathematical Simulation of a Manned Space Mission in chapter IV describes a large-scale mathematical model used to simulate the Manned Orbital Research Laboratory. Similar simulation techniques could be adopted to study many manpower intensive facilities in industry.

The real problem surrounding these complex manpower intensive facilities is that facility design and subsequent manpower scheduling are closely interrelated. The facility cannot be adequately designed without knowledge of the availability of manpower and requisite skills, and the manpower skills cannot be scheduled and analyzed without knowledge of the facility design. In simpler terms, the man-machine interface leads to the major unsolved problems in designing manufacturing processes. The simulation developed with NASA funding approaches these problems in several steps. First, a preliminary requirements model is used to assess the feasibility of particular operations and to select the manpower (in terms of numbers and skills) which will be necessary for these operations. Second, the planning model is used to perform all the scheduling and logistics functions associated with the particular operations and the particular crew developed by the preliminary requirements model. Finally, the full-scale simulation model is used to determine the effects of various contingencies on the nominal man-machine design. Nonstandard equipment failures are simulated, and their effects on the crew are determined. Human failures and illnesses are simulated to determine their effects on the scheduling problems. The use of this full-scale simulation model may reveal numerous problems arising from the man-machine interface which would otherwise go unnoticed. The nominal design can then be altered to provide for the contingencies revealed by the simulation. This same three-stage approach to the analysis and simulation of manpower intensive functions can be employed profitably by industrial corporations in the design of manufacturing facilities. This approach will allow concurrent study and solution of the problems associated with facilities design and manpower scheduling in a manufacturing process.

Another systems technique developed with NASA funding deals with the problems of redundant system design and could be used in the design of certain specialized production facilities. In some manufacturing processes, notably assembly line processes, redundant functions, equipment, and personnel are added to insure the smooth and uninterrupted flow of the work. The addition of these redundancies is obviously costly and must be controlled to avoid excessive staffing and idle equipment time. At some point, the incremental cost of the redundancy will exceed the expected loss due to an interruption of workflow, in which case the redundancy should not be added. Studies must be conducted to yield data for the trade-off decisions surrounding the addition of each new redundant function or man to the manufacturing process.

A specialized technique for dealing with the problems of redundant system design was developed by the General Electric Co. with the aid of NASA funding. This technique is described briefly in Mission Optimization Via the Selection of Redundancy in chapter IV. The basic approach of this technique is a cost-effectiveness model in the context of systems redundancies, so that each conceivable combination of redundancies can be analyzed for its contribution to overall system reliability. As a first step, a baseline design system is postulated which includes those elements and only those elements which can perform all necessary functions when everything operates perfectly. Redundancies are then selectively added to this system, and the overall reliability is progressively increased. The process is continued until all reasonable combinations of redundant elements are considered. A form of dynamic programing is then used to choose the optimal combination of redundancies on the basis of a cost-effectiveness criteria. This type of approach is useful because it considers the systematic effects of many combinations of redundant additions, instead of analyzing each possible addition by itself. Because it can consider the interaction of redundant elements, it can be a major improvement in the design of assembly line operations or similar manufacturing processes.

The Application of Systems Techniques to Cost Estimation and Cost Control

Introduction

The problems of cost estimation and cost control provide opportunities for the utilization of quantitative management methods. Fortunately, costs have been naturally quantified into a single numéraire, dollars, so that they may be conveniently analyzed and processed by quantitative systems techniques. There are many specialized models which have been used for particular problems in the area of cost control or relevant cost analysis. This survey report will not attempt to describe all these specialized mathematical models, but will concentrate on the use of systems techniques in two general and crucial problem areas.

A Systems Approach to Cost Estimation

The estimation of future costs is a recurring corporate function. All planning procedures require adequate cost data before the strategic decisionmaking process can begin. Given the central importance of these cost estimates, how do corporations establish cost-estimating procedures? The procedures used by some firms can seriously distort corporate decisionmaking. In fact, standard procedures for cost estimation are never really established in many corporations, and cost estimates are made rather haphazardly as the need arises. The various cost estimates emerging from a haphazard process are often the product of different methods of estimation, different assumptions, and different people. This lack of underlying consistency is very unsatisfactory from the decisionmaker's point of view. Many of the decisions a firm must make will ultimately boil down to a choice between mutually exclusive alternatives. This choice should be made on the basis of consistent cost estimates. It is necessary, therefore, to develop a set of cost-estimating procedures which can, at the very least, provide a consistent basis for comparing alternative decisions. Furthermore, the cost-estimating techniques should be reasonably flexible so they can produce cost estimates on many different types of proposed projects. Finally, it would be desirable to have as efficient a set of cost-estimating programs as the task allows. The criteria used to evaluate cost-estimating systems, therefore, should be consistency, flexibility, and efficiency.

NASA has been confronted with these same cost-estimation problems for each project that it has undertaken. As the space program has progressed, reasonably sophisticated and efficient cost-estimating procedures have been developed to solve these problems. An excellent example of a cost-estimating system developed with NASA funding is described in The Manned Spacecraft Cost Model in chapter IV. These same methods can be altered for utilization by large industrial corporations. The basic steps can be as follows:

(1) Take the basic systems whose costs must be estimated, and break them down into subsystems, assemblies, components, etc.

(2) Continue this breakdown until the level most convenient for cost estimation is reached

(3) Characterize the units on this level in terms of all relevant parameters, e.g., weight, personnel, performance variables, etc.

(4) For each of these units, develop "Cost-Estimating Relationships" (CER's) which express cost as a function of the above parameters

(5) Store these CER's in a data library for use with the computer system

(6) Build a computer program which, given a description of the system whose cost must be estimated, will call the appropriate CER's and assemble the results into overall cost estimates

Using this basic framework, it is possible to overlay several sophisticated techniques, such as contingency costing systems. The advantages of the costing system outlined above are as follows:

(1) If designed properly, the elements of the CER library will be flexible enough to accommodate many diverse cost-estimating jobs

(2) The CER library establishes a common set of costing relationships, so that the resultant estimates are consistent among themselves

(3) The automation of the system provides an efficient time-saving approach to the problems of cost estimation

Of course, the success of the system depends on the accuracy of the individual CER's. These CER's can be as complex or as simple as the problem allows. For example, accurate costing relationships can often be generated by multivariate regression analysis using historical cost data. Or alternatively, simple formulas or rules of thumb may be generated for some units.

This type of systematic and efficient approach to costing seems particularly appropriate for large processes or manufacturing industries with reasonably stable manufacturing techniques. It may be useful whenever cost-estimation problems arise frequently enough to warrant the expense of developing a consistent but flexible cost-estimating system.

A Systems Approach to Cost Control

Effective cost control requires an efficient set of management techniques incorporated into an overall cost-control system. Elements of a management information system are needed to transmit the required cost data; analytical techniques are needed to perform the relevant cost analyses: and elements of a management control system are needed to assure goal congruence for the entire system. Techniques for effective control are particularly necessary in large, diverse, but organizationally centralized, corporations. In response to a quite different set of project-oriented problems, NASA has developed a management information and control system which could be readily adapted into a set of techniques for cost control. NASA's system is called Forecasts and Appraisals for Management Evaluation (FAME). This system was developed as a technique for monitoring, forecasting, and evaluating weight-control data for the entire Apollo spacecraft. With minor adaptations, this same system structure could be used to monitor, forecast, and evaluate cost-control data in a large corporate enterprise.

Techniques for monitoring cost data with automatic data-processing equipment are already being used in many industries. But the concept of forecasting trends in operating costs on the basis of current cost data, and combining these forecasts and their evaluation into an overall cost-control system, is relatively new. A new cost-control system similar in structure to the FAME system could be used. All relevant cost data would be collected at regular periodic intervals and compiled into a historical time series. This might be done daily, weekly, or monthly, depending on the time dependence of the cost data being analyzed. The cost-control system would then process these data and perform the bookkeeping and reporting functions necessary for its transmittal. The forecasting module would then analyze the data and, on the basis of historical trends, forecast relevant cost data into future time periods. A number of different forecasting techniques are available with the FAME system, and one or several of these techniques might be selected for each cost parameter. On the basis of the current cost levels and the forecasted costs, the system would automatically yield a signal to management when a cost deviated or appeared to be ready to deviate from a preselected set of control limits. The system could be structured in such a way that it would automatically assess the "criticality" of any deviation from the control limits. A reasonable criterion for evaluating this criticality in a corporate enterprise might be the final effect on corporate profits. The system would then forecast costs, point out any expected deviation from the control limits, and automatically assess the effect of these deviations on the total profit picture of the corporation.

The development and implementation of this type of comprehensive cost-control system would be an ambitious undertaking, but the benefits might well justify the expense. It could provide timely recognition of dangerous cost trends before those trends could have a large effect on profits. Because the system would be automated, it would relieve management of many time-consuming tasks. Perhaps most important, it would replace outmoded haphazard costing methods now in use in many business enterprises. Because costing techniques must be adapted carefully to particular problems at hand, this section has dealt with these costing systems in very general terms. Readers interested in the potential utilization of these costing systems should study both the later sections of this survey and the source documents referenced.

Market Research and Marketing Information Systems

Market research is that corporate function which attempts to ascertain the past, present, and future purchasing habits of potential consumers. The collection and analysis of market data is an integral part of this function. The large amount of quantitative data which must be handled provides ample opportunity for the productive use of systems techniques in several important problem areas.

One of the most important tasks facing a marketing organization is the generation of an overall strategy for the introduction of new products. This involves the marketing research function itself, the test marketing phase, and finally the full-scale marketing effort. The following questions arise in the new product introduction cycle:

(1) Have we done enough market research?

(2) On the basis of market research data, should we drop, alter, or retest the product concept?

(3) Should we test-market at all?

(4) How large and how long should the test market be?

(5) On the basis of the test market, should we proceed with a full-scale product introduction?

Although the final basis for these decisions must be the judgment of the marketing organization, statistical decision theory may be a valuable aid. Statistical decision techniques may be used to order these decisions into a systematic and, more importantly, a consistent framework from which marketing managers may proceed. All too often these crucial decisions have been made on a piecemeal basis, and by different managers, so that the overall strategy for product introduction has been far less than optimal. If, for example, a test marketing phase is dependent upon the results of market research data, the function of market research must be designed with prior knowledge of this dependence. If a full-scale marketing phase is dependent upon the results of the test market, the test market must be designed with prior knowledge of this dependence. The potential benefits to be derived from any one of these phases is tightly bound to the overall coordination of the product introduction cycle. Statistical decision theory can force managers to take explicit account of the interrelationships which lead to this requirement for coordination.

For example, decision techniques will formulate the new product introduction in the following way. First, a decision tree is structured to model the interdependencies as illustrated in figure 1. Starting from the future time periods, decision-makers must specify what they will do if a particular test market result occurs. Working backward through the decision diagram, they must also specify their future action if a particular market research result occurs. Finally, they must assign prior probabilities for the occurrence of these particular test marketing and market research results. Armed with this information, various overall strategies of new product introduction can be evaluated and the optimal strategy chosen.

This kind of analysis can be particularly useful to a corporation in which new product introduction procedures have become too routine. The test marketing phase, for example, is often undertaken needlessly, at the expense of both money and leadtime over competition. The benefits of the test marketing phase can be estimated by using the following decision-theory techniques:

(1) Conclude what future action will be taken for all possible test market results

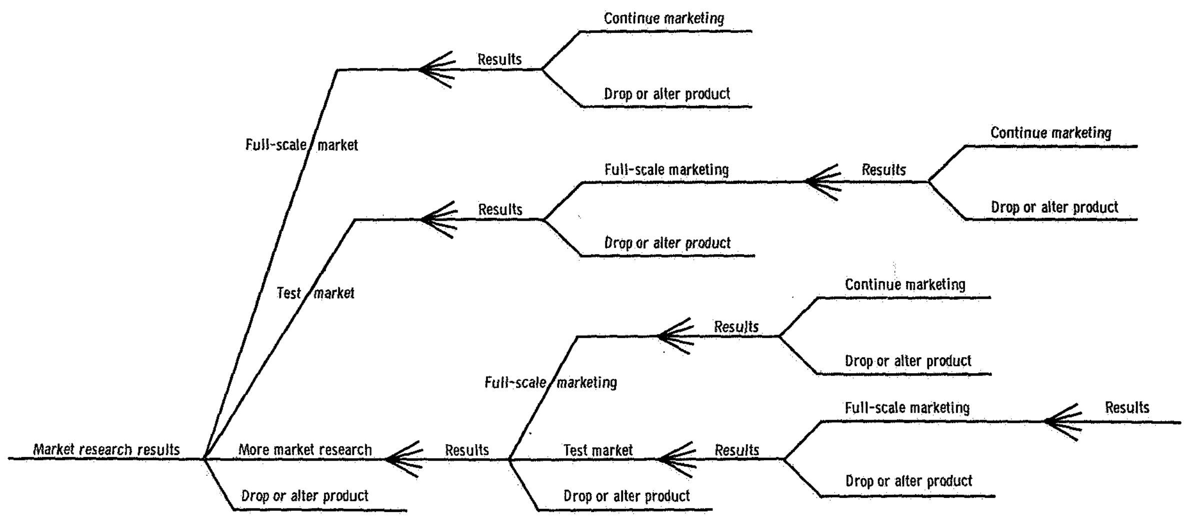

FIGURE 1.—A decision theory diagram for new product introduction.

(2) Estimate the prior probability of these test market results

(3) Calculate the expected value of the test marketing phase. If the expected value of the test marketing data is less than the expenses incurred, marketing managers should think very seriously before proceeding directly with full-scale product marketing.

In a similar way, decision techniques can be used to evaluate all phases of the product introduction cycle. Properly employed, these techniques help specify marketing strategies which are not only coherent and consistent, but optimal from the overall corporation point of view. These techniques have been used in connection with NASA-funded projects to formulate optimal strategies for complex problems in space program management. The application of these same techniques to the formulation of marketing strategy has great potential for many industries.

At the heart of the market research assignment is the difficult task of predicting future sales volume. Quantitative management tools can be used effectively in this problem area. Consider a large corporation with many existing products established in markets across the country. Historical data describing sales volume for these products is usually available, though perhaps not in systematic form. A total marketing information system can be employed to derive maximum benefits from these sales data. What is really needed is a market information system that automatically collects, processes, and analyzes these data for historical trends. On the basis of these trends, forecasts can be generated, and the consequences of these forecasts can be described for management's perusal. All this can be done in a large corporation within the marketing information system itself. The information system can then present an automatic, complete, and systematic view of sales and sales forecasts for use by marketing management, but the establishment of such a complete data and sales forecasting system can be a prodigious task. An excellent example of this kind of management system is the FAME system developed for the Apollo program. The FAME system is concerned with monitoring and forecasting spacecraft weights instead of sales, but the same principles of data handling and analysis apply. A system like FAME can be easily modified to form the basis for an effective marketing information system.

Because the FAME system is described in the next chapter, the following paragraphs will not dwell at length on its characteristics, but will describe how the sales forecasting problem should be structured for use in the marketing information system. First, the existing historical sales data should be collected and classified according to product, geographical region, and cognizant sales office. This breakdown for classification should continue until all relevant data groups that are worth monitoring have been identified. An upward-flowing information system should then be organized to permit the systematic collection of current data at regular time intervals, probably monthly or weekly. The forecasting techniques which provide the most accurate estimates of future sales must then be determined. The FAME system utilizes four different and reasonably sophisticated forecasting techniques. A corporation may wish to retain these techniques, or add modifications of its own which are better suited to the individual data streams. Finally, the effects of different future sales levels must be determined beforehand, so that the marketing information system can automatically give some indication of the criticality of its results.

Once these initial determinations are completed, the marketing information system can be introduced in much the same manner as the FAME system. Periodic sales can be analyzed automatically and projected by product, sales region, and sales organization. Departures from either standard or desired performance can be ascertained before the sales volume has had an opportunity to slump too drastically. The total marketing effort for products or regions with lagging sales can be singled out and corrected before overall sales activity is affected. The system can provide for timely recognition of both favorable and unfavorable sales trends, and can automatically suggest the criticality of these trends. The system is thus a valuable tool to aid marketing management in its decisionmaking function.

The marketing information system can also be extended to monitor salient parameters which describe the market environment in which the firm operates. For example, a time-series of data describing demographic characteristics of a firm's customers can be input data for the information system. Data describing the firm's competitors, their sales, their advertising coverage, etc., can be input data for the system. Total primary demand data and market share data can also be included. Indeed, any time-series of data relevant to the market research function can be handled automatically by this system. Upon special demand, the computer-based system could furnish total market projections for use in evaluating the potential of new product innovations. The system could therefore be used not only as an information and control system, but as a valuable aid to the marketing research function. Although such a system must be specifically adapted to the particular needs of a corporation, the basic framework of the FAME system is clearly applicable. This basic framework provides building blocks upon which the total marketing information system and research function could be established.

The Management of Research and Development

The selection and management of research and development (R&D) projects are crucial to technology-based industries because of the long leadtimes associated with product development. The planning and management of R&D can be considered in the following sequence:

(1) Identification of objectives

(2) Estimation of the expected benefits of each project

(3) Estimation of the expected costs of each project

(4) Project selection

(5) Estimation of current and future manpower, funding, and facility requirements

(6) Project management

The techniques developed in several of the NASA models and simulations can be used in this sequence.

Identification of Objectives

The problems involved in identifying corporate objectives are many, and the techniques of statistical decision theory described in the next chapter may be helpful in arriving at a set of objectives. The decision tree analysis may be useful in tracing out possible consequences of establishing certain objectives. The use of utility theory may be helpful in refining the preferences of corporate planners. Assuming that these objectives can be obtained, they must be translated into their significance for the research and development program. This translation process should be straightforward, logical, and not very time consuming since corporate and intermediate objectives tend to change. The translation procedures must be sufficiently responsive to determine the impact of the changes on the R&D program and to provide feedback estimating the influence of the changes on the new objectives.

The mission success evaluation model developed by the Jet Propulsion Laboratory (JPL) uses a procedure for translating broad objectives into more detailed requirements for specific missions. A hierarchical structure, along with procedures for deriving weighting factors for each of the elements within the hierarchy, was established to make this transition. Within a corporate context, broad objectives may be supported by several product lines with a variety of technological characteristics. The research and development program may be used to make improvements in those characteristics in anticipation of introducing new products. These relationships can be structured into the weighted hierarchy procedures developed by JPL.

The JPL model was used to identify a set of weighted objectives for the R&D program. The process can be continued by subjectively determining the relative contribution of each proposed R&D project to each of the weighted objectives. The value of each proposed project can then be calculated by summing the products of its contribution to each objective times the weight of the objective.

Estimation of the Expected Costs of Each Project

Costs of individual projects can be estimated on the basis of past experience with similar projects. The cost model developed for NASA by General Dynamics (see The Manned Spacecraft Cost Model in ch. IV) would be useful for estimating the total costs for product development. The model can estimate how costs will be distributed over time and how they will be affected by various contingencies. The model would need to be adjusted for the industry and products involved by changing the CER's in the model library. Those relationships show how cost has varied with the performance of product components in the recent past.

The cost model can also assess the effects of unforeseen contingencies on the cost estimates, such as:

(1) Program delays due to technological problems

(2) Periodic budget constraints

(3) Cancellation of any part of the development program

(4) Substitution of alternative product components

(5) Accelerating the development schedule

(6) Development of more than one component to perform a function

Project Selection

Given the expected benefits and costs of all R&D project candidates, the "best" ones can be selected in a variety of ways. If there is a single value and cost for each project, and a single budgetary constraint, the selection can be made by simply ordering the projects according to their value-cost ratios and selecting them in order until the budgetary constraint is met. However, the situation in the real world is rarely that simple. There is usually more than one way of accomplishing each project, with the result that both value and costs change. There is usually more than one kind of resource involved in the categories of funds, manpower, and facilities. Plans often must be made for more than 1 year and budgetary demands spread somewhat evenly over the planning period. Such situations require the use of mathematical programing techniques to arrive at the best selection of R&D projects.

The NASA-GE-Voyager model is a technique used to solve a similarly structured problem. It uses a dynamic programing formulation to search through a very large number of combinations of components and subsystems to arrive at the total program combination that would maximize the total value of the mission. Similarly, such a program could be used to search through many combinations of R&D projects to arrive at the one maximizing the total value to the corporation within the constraints of the budget.

Estimation of Manpower, Funding, and Facility Requirements

The management of research and development includes the problem of estimating resource requirements in the near term for the R&D program and in the far term for the corporation. The Texas A&M probabilistic long-range planning models, the General Dynamics cost model, and the General Dynamics scheduling model for the Manned Orbiting Research Laboratory are NASA models which can assist in solving this problem.

The Texas A&M work on long-range probabilistic planning (see Probabilistic Long-Range Planning in ch. IV) is directly applicable. Manpower requirements for each R&D project can be estimated, along with the probabilities of project success. When this information is assembled for all projects with their various schedules, resource requirements, and success probabilities, long-range forecasts of total resource needs can be made. The study describes procedures for estimating resource needs, obtaining subjective probabilities for follow-on project initiation, and applying probability distributions for determining the starting period of the proposed projects. These procedures can be used for long-range planning of manpower, funding, and facility requirements.

The General Dynamics cost model is most useful here in its contingency planning mode. The model predicts the distribution of resources required by a proposed product development program over time, and assesses the impact on this distribution caused by such contingencies as delays in progress due to technological difficulties, budget constraints, schedule accelerations, and other factors.

The General Dynamics scheduling model for the Manned Orbiting Research Laboratory (MORL) is most useful in this context for estimating short term resource requirements. The techniques developed for this model can be used for an R&D laboratory. The model matches the skills of experimenters with the skills required by experiments, thereby identifying quantitative and qualitative requirements for manpower and how these requirements might be changed by unforeseen breakdowns of experimental equipment.

Project Management

NASA and the aerospace industry have made major contributions to the scheduling and management of large-scale projects made up of many interrelated, time-critical activities. The General Dynamics scheduling model for MORL described above can be used not only for estimating resource requirements, but also for managing daily schedules for a large, multiproject R&D laboratory. Optimal rescheduling of experiments as a result of several kinds of contingencies, such as staff illnesses, vacations, equipment failures, and experimental difficulties, can be accomplished.

The FAME information and control system developed for the Apollo program can be used for monitoring the progress of a development program. When the R&D program is directed toward improving a particular product characteristic that can be measured quantitatively, the numerical value of the characteristic can be tracked during the development program. The trend in the value of this characteristic as it changes during the program is tracked by the model, and forecasts of its value at the end of the program are made. FAME is a complete system of gathering and processing program data, identifying current and predicted future status, pointing out program areas, and suggesting trade-offs that could be made to alleviate the problems.

The contingency planning mode of the General Dynamics cost model can also be used for project management. The model receives program inputs regarding the starting and finishing times of activities that must be accomplished. Using the expenditure patterns of similar historical activities, the model forecasts the expenditures required as a function of time. Manpower data can be handled in a similar manner. The model can then provide the cost implications in both funds and manpower of the various contingencies described earlier, such as technological stretchouts, changes in budgetary constraints, schedule changes, etc.

Good project management requires skilled managers as well as appropriate information systems. NASA's Goddard Space Flight Center has developed a simulation of the R&D project management process that was designed to train managers. It is used to provide management experience in an environment where mistakes in judgment are not as costly as they would be in the real situation. The exercise, a management game called GREMEX, is described in the part entitled GREMEX in chapter IV. This management exercise can be used both for evaluating and selecting project managers and evaluating proposed changes in the project management information system.

With respect to the management of research and development, the most significant contributions of NASA modeling and simulation techniques are the operational combination of qualitative and quantitative information in coherent frameworks.

Many of the goals and objectives of R&D programs must be expressed in qualitative terms. NASA modeling efforts have developed procedures for structuring qualitative information into weighted objectives and using them to make choices between technical alternatives. Hierarchical structuring and statistical decision theory have been used to translate broad guidelines into parameters of value that are meaningful for the evaluation of diverse technical characteristics. These developments were appropriate and necessary to administer an enterprise as costly as the national space program. These same models and techniques can be adapted by large corporations to fit the particular needs of their own R&D programs.

THE APPLICATION OF SYSTEMS TECHNIQUES IN THE PUBLIC SECTOR

Systems Techniques in Urban and Regional Planning

Introduction

Urban planners face mammoth multivariate problems, the complexity of which often far exceeds men's expectations. This section will suggest potential areas of application for NASA developed "systems" oriented techniques. Reference 2 describes these potential applications of aerospace technology. Hopefully, the transfer and successful implementation of relevant systems techniques will provide new insights for the large national effort devoted to exploring, testing, and implementing programs to cope with the problems of the cities.

The systems concept is based on the premise that the activity under analysis must be viewed as a system of interrelated activities. Experience has shown that there are intricate interrelationships between a city's physical, social, psychological, and economic problems. Hence, it has become increasingly obvious that solutions to many urban problems can be obtained only by carefully coordinating improvements in many components of the system.

Systems analysis emphasizes that there is an ultimate objective to every system and that the attainment of this objective is more important than achieving minute gains toward subordinate objectives. If the objective of an urban renewal program is to improve the quality of housing available to all income groups in the city, this goal must not be sacrificed to increase the supply of housing available for one specific income group. Clearance and redevelopment of a slum area should not exacerbate the growth of slums in other areas.

Statistical Decision Theory and Techniques

Statistical decision techniques should be helpful in analyzing urban problems and the underlying causes of such problems. A probabilistically derived set of ratios expressing vacancy rates in rental housing, persons per room, housing reference, discretionary income, and other relevant variables might be combined to form useful leading series that would facilitate prediction of housing trends. This might be done even if the precise lines of causation were not fully articulated. Decision-theory techniques also might be used to obtain subjective estimates of the answers to extremely difficult questions such as: What is the probability of a "white exodus" from an apartment complex given the admittance of a Negro family? Or, what is the causal relationship between family formation, housing characteristics, and income level?

A subjectively derived decision rule could provide that if the housing-to-stock-to-household ratio should drop below some derived local historical value and/or some regional or national figure, slum clearance projects involving demolition of housing would continue only if accompanied by a rate of new construction in excess of family formation.

There is a need to identify and quantify some cumulative external-economies function that produces a simulated "accelerator" or "multiplier" effect, where public investment in new housing, parks, and other public works induce private investment in new housing and other facilities. The renewal process is so subtle that no single coefficient can express the accelerator effect under all sets of circumstances. The renewal-accelerator function is almost surely a stochastic one in which there is a set of probabilities associated with various site plans. One can try to obtain a higher probable leverage on private investment only by running a greater probability of failure—loss of public investment. For example, an L-shaped project would have greater leverage (private response) if it were successfully established and the L were filled in to complete the square. A U-shaped project would be more conservative in that the fully encircled area would be more likely to be rebuilt than the only partially encircled area inside an open L; but while the probability of success might be higher, the probable gain could be smaller. While the plan which offers the highest probable payoff is clearly a prime candidate among the many alternatives, there are other possible strategies which cannot be rejected offhand, such as the minimization of total loss with some given level of leverage. The O-shape might promise modest leverage with minimum probability of failure.

Highly complex objectives become more manageable if plans can be changed during the course of a project. Otherwise there is a strong tendency toward conservative design; i.e., solidly filling the renewal area for fear of failure if a section of the environment is left unchanged. The techniques of Bayesian statistics, decision trees, and utility preferences can be combined to develop a sequential decision diagram, describing various alternative acts and events. If a once-and-for-all commitment is not binding, sequential decisions can be made as needed until a self-regenerative process evolves. Publicly subsidized housing decisions (the amount, where, and to whom) could be reevaluated using updated decision tree information as soon as private housing was stimulated. The cut in subsidized housing payments could be transferred to a new area as seed money to begin the cycle again. This site planning technique could yield substantial savings.

Probability techniques could also be utilized to build a model which would simulate the processes of industrial or residential development. The allocation process, developed as a submodel for a larger model simulating the growth and development of a metropolitan area, could use Monte Carlo or other statistical techniques to produce the final allocation. The model developer would construct a logically consistent conceptual framework, utilize constraints that correspond to some probabilistically derived behavior, and incorporate feedback loops to simulate behavior over time. The locational decisions of firms, governments, and households would have to be researched and verified, probably using some combination of objective and subjective preference analysis. The land development process would similarly have to be investigated to determine what land was available, the quantity, and the time new land would become usable. Then, given the land available and the location decisions of the user, a probabilistic algorithm could be employed to allocate the land user to available land. This is essentially a matching or scheduling problem which can be approached with simulation techniques similar to those discussed in Mathematical Simulation of a Manned Space Mission in chapter IV.

An alternative use for this program would match potential buyers and sellers of land to simulate the local real estate market. The seller of land generally desires to maximize total revenue, while buyers strive to maximize satisfaction or utility consistent with some level of income. The buyer's satisfaction is influenced by the distance from city core, the distance from work location, local educational facilities, street accessibility, sewage, size of plot purchase, etc. On the other hand, the seller's position is influenced by exogenous features such as accessibility to the site for potential customers, the number and types of competitors, and consumer demand for land. Few of the above variables are easily quantifiable, which suggests the application of assessment and simulation techniques. A combination of these techniques could test the impact of alternative public policy or program changes.

Simulation Techniques

General simulation techniques can similarly be used to obtain answers to many of today's complex urban planning problems. Some schematic process is needed to describe and predict the mobility of the poor. Another puzzling problem concerns code enforcement and its effect on the supply of adequate dwelling units available within a city. The recent debate over the best approach to the low-income housing problem is ideal for simulation. One can investigate construction costs, amortization methods, operating expenses, and rent paying ability to develop causal and independent relationships. Then, given a point in time, one can test the effect of rent subsidies, construction subsidies, land write down programs, or tax incentive plans on the supply and demand for low-income housing. In sum, general simulation techniques can be applied to almost any quantitative approach describing and analyzing the process of urban growth and development. A whole series of government actions (i.e., zoning, code enforcement, rent subsidies, etc.) can be tested by building and utilizing quantitative models.

In analyzing urban planning one is bewildered by the complex interrelationships of different programs. We have learned that a slum is a complex social mechanism of supportive institutions, housing submarkets, and human resources, intertwined with the metropolitan community as a whole. Decisions by governments, firms, and individuals in metropolitan areas are affected by interdependent spatial systems such as the use of recreation facilities, transportation and communication networks, and the markets for land, housing, and labor. The rapid evolution of a genus of mathematical techniques or models to predict conditionally certain locational aspects of the behavior of urban populations has responded to these complexities.

The simulation model builders must be able to perceive repetitive temporal patterns in the processes of urban life. Once these relationships are identified, they can be systematically used as building blocks or elements within the model. These elements can be combined and manipulated by the model to generate larger, quasi-unique patterns of urban growth and development which resemble those of the real world.

The Application of Probabilistic Long-Range Planning

Probabilistic long-range planning methodology can be used to plan construction of low-income housing projects. The construction of dwelling units is generally a uniform process, and the number of projects accepted or rejected by one construction organization is a function of its ability to construct and manage profitably a large number of discrete projects. A "forecasted manpower matrix" can be filled with columns containing worker characteristics necessary for land clearing, foundation laying, brick laying, landscaping, etc. The matrix rows can be occupied by dates corresponding to time periods needed for completion of various construction activities. Given the matrix, manpower requirements can be generated mathematically. Management can then utilize existing production techniques such as material sequencing, heuristic line balancing, and job shop scheduling to complement the information generated by the manpower matrix. The result could be increased efficiency and lower construction costs.

The Use of Probabilistic Planning Models for "New Town" Development

Probabilistic planning models can also aid in the development of "new towns." Over the next 30 years the United States will have to double its stock of residential housing. In response to this need, planned communities and new towns have been organized by private land developers. These developments are more than housing subdivisions with an occasional shopping center; they are attempts to build entire communities. They are planned and built as self-contained units, and they often include commercial and industrial areas interspersed with the residential communities.

The new town represents a total planning effort. The developer gathers specialists from many disciplines to define goals, describe the system known as the city, and develop a land-use pattern. This written program and land-use pattern must then be transformed into a community. Commercial, political, recreational, social, and educational facilities must be incorporated into the community plan. The development program must not be a fixed plan with a static relationship between the parts, but a framework for continuous urban growth, for the success of the project depends on the flexibility of its parts. Each element must be designed, integrated, and implemented within the program for a viable community, if the urban form is to be responsive to human needs.

The role of the new town developer becomes twofold. First, he must plan then he must implement the plan. He must estimate the present and future needs for homes, schools, social service, churches, shops, recreation, factories, warehouses, actual business functions, and their physical requirements of capital services. He must plan growth in response to these uncertain future needs.

The implementation plan is used to determine the best timing sequence to effect systems design, methods of financing, and development of the system. The total plan becomes project oriented with total success dependent upon the smaller project efforts. The projects of the new town are then allocated to planning phases or growth stages with construction activity staged over time, and numerous subcontractors concentrating on elements of the plan.

The Program Evaluation Research Task (PERT) and the Critical Path Movement (CPM) systems have been used by NASA contractors to monitor and plan their schedules. Computer programs have been developed to choose the critical events or activities which must be completed by a given date for a project to be successfully concluded on schedule. The builder must define all activities and events, their sequence, interdependence, and the expected time distribution of start and finish. With these inputs, PERT and CPM systems can derive optimal scheduling plans.

The long-range probabilistic planning model developed by NASA can also be used by developers to plan urban development and maintain control of a project. Developers may use this long-range planning model to structure their resource requirements as a function of time. The developers can use the model to schedule resource allocation and shipments for the total project including all the work of individual subcontractors. To implement this system, each subcontractor must estimate his resource requirements of labor and materials from the CPM analysis of the project. This information can be forwarded to the developer in a matrix format of labor and materials requirements for each time period.

Labor Resources				*Material Resources*			
Architect				Cement			
Carpenter				Fuel			
Painter				Wood			
Plumber				Steel			
	1	2	3		1	2	3
	Time phase, weeks				Time phase, weeks		

The developer in charge of a total new town plan then can use the techniques of probabilistic long-range planning to aggregate this information for the individual projects into a total matrix of resource requirements. This will require assessments of the subjective probability distributions for the starting dates of each project. With this summary of needs he can monitor the total supply of labor and materials, and insure smooth construction activity. The developer can then take advantage of economies of scale by centralizing materials shipments to the site and organizing the labor force for continuing onsite employment.

Cost-Estimation Techniques

A systematic procedure for estimating the cost of various urban renewal alternatives should be developed. At present, costs are usually underestimated by a large percentage. When legislative bodies are called on for additional funds to complete a renewal program or project, they often respond negatively. Creative and constructive work often is inhibited by the unavailability of capital. The cost-estimating techniques developed with NASA funding can be used to generate more accurate cost analysis for further urban renewal projects.

Other Probabilistic Methods

Probabilistic techniques might similarly be employed to predict the condition of aging residential and nonresidential structures. One could classify structures as good, in need of minor repair, in need of major repair, or untenable (requiring destruction or complete rebuilding). Over time, structures tend to pass from one condition to another. The deterioration rate is a function of many variables such as whether structures are owner- or tenant-occupied, number of families, incomes of occupants, and age of the structures. The causal relationship between these variables and the condition of housing could be derived by statistical techniques (i.e., regression, correlation, functional analysis) or subjective probability methods. The condition of structures could then be predicted by using Monte Carlo methods or Markov chains. This use of applied mathematics and similar techniques could be called "urban science," analogous to the "management science" of business corporations.

Optimizing Models

If optimizing models, similar to those developed with NASA funding, were used to structure and solve urban planning problems, one of the greatest benefits might be clearer formulation and precise definition of urban planning goals and objectives. Because city planning commissioners often describe their objectives vaguely or abstractly, the pragmatic planner who develops and implements programs is often confused and inhibited. He is faced with the onerous task of developing algorithms to test alternative public policies and programs, the substances of which are clouded by political objectives, personal goals, feasibility, social acceptability, and usefulness to the city's inhabitants.

The application of optimizing techniques to urban problems may adopt many forms. A linear programing approach could be employed to simulate residential location where the objective function to be maximized would be aggregate rent paying ability subject to certain constraints. Industrial or residential developers could also use either linear or nonlinear programing to quantify "develop or not develop" decisions. In this instance, the objective function would minimize the cost of developing land subject to constraints such as demand for various types of land, zoning restrictions, and land-use characteristics.

Other potential areas for uses of optimizing techniques include: (a) The routing and scheduling of rubbish collection; (b) Determination of the optimal enforcement staff for a housing code; (c) Fire station location, where a trade-off must be made between a large number of small stations or a small number of large stations; and (d) Law enforcement where the optimizer is concerned with response times and coverage, but is subject to specified budget constraints.

Project Management

The aerospace project management approach to the administration of large, complex contracts can be used to direct and control urban and social contracts. In both areas, management must cope with a large number of complex and interrelated variables, continually evaluate programs and make conditional decisions in response to a rapidly changing environment, maintain strict budgetary control, and be responsible and sensitive to changes in public policy. The transfer both of technical know-how related to project management and of the techniques for training and educating potential urban project managers is feasible.

Management Control and Information Systems

The management control and information techniques developed by NASA and business may also be utilized by tomorrow's urban planners. The monitoring, evaluation, and control of urban programs is necessary to insure that the programs are truly effective. City renewal programs have historically been characterized by massive accumulation and distribution of documents and data, the creation of an inefficient and cumbersome bureaucratic structure, and lack of any workable feedback mechanism to signal the restructuring of thought on the basis of empirical results. Such characteristics might be changed by creation of city data banks, better determination of what information to record, study of what activities should be monitored and in what form data should be displayed for these activities, analysis to determine who should receive the reports and with what frequency reports should be circulated, and what role the computer should assume in the day-to-day administration of city and regional affairs. Implementation of the above could reduce many valid complaints.

Systems Concepts in Transportation Planning

Introduction

Because of the long leadtime required for the construction of transportation facilities, planning in some form is inescapable in the development of a transportation system, and some of the essential ingredients of systems analytic procedures are already in use. Requirements have been determined, route location alternatives have been compared, and comparisons of costs and benefits have been made. Early planning studies were characteristically focused rather narrowly on determining capacities required to satisfy current and estimated future needs without taking note of the multiplicity of impacts of investments in transportation facilities. More recent transport systems analysis and planning has been broader and has drawn upon sophisticated techniques of operations analysis and economics.

Urban Transportation Planning

Because urban transportation problems have become increasingly acute, it is not surprising that the development of systematic transportation planning procedures have advanced most rapidly in this field.

Pioneering studies were conducted in the Detroit and Chicago metropolitan areas in the 1950's. Although these were not the first such studies, the staffs made significant innovations in the analysis and forecasting of traffic flows in existing and proposed urban transportation networks. Both studies also made important contributions to the use of data-processing technology in transportation planning. The Penn Jersey Transportation Study, concerned with the Philadelphia and Trenton Metropolitan areas, carried the process a step further by focusing on the relationship between transportation and land development. The attempts by the Penn Jersey staff to make quite sophisticated models operational clarified many of the critical problems in the construction of such models. In the context of that study, the first attempt was made to develop systematically and to test and evaluate alternate transportation plans for the metropolitan region. Other studies had looked at alternatives but had made little effort to develop techniques for deriving them systematically.

Technique of Urban Transportation Analysis

Typically, the planning horizon for metropolitan transportation studies is 25 years. The basic orientation is thus toward long-range planning, but recommendations for immediate implementation are generally made and an intermediate (15-year) plan is also developed.

Metropolitan planning studies are based on detailed cross-sectional analyses of population, economic activities, land use, and traffic flows on the existing network within the metropolis and its surrounding area. Models are used to forecast population and economic activity levels and patterns of land development. Forecasts of future travel demand (trip generation) between small subareas of the metropolitan area are based on adjusted rates derived from current patterns. The determination of the modal split is generally a two-step procedure, first between automobile and mass transit, and then between the means of mass transit if more than one is present. Future travel is then assigned to the alternative future networks which have been developed separately through the use of a variety of procedures including generally some form of sketch planning. Comparative evaluation of the network alternatives is then made. In some studies, the operation of the system of models is made iterative, so that the effects of the introduction of new transportation facilities on land use can be taken into account.

Large-Scale Transport Systems Analysis and Planning

Analysis and planning for intercity and international transportation requirements tended to be confined to single mode emphases, with concern about the deterioration of rail service between Boston and Washington, led to some initial studies of expected demand for intercity travel in that region. These studies were the forerunners of the Northeast Corridor Transportation Project. Concerned with all modes of transportation, the corridor project was an attempt to apply a systems analytic approach to a regional transportation problem. The corridor, as defined for the study, extends from southern New Hampshire to central Virginia, and includes virtually all of the area to the east of Appalachia.

The problem was to determine regional intercity transportation requirements for 1980 and 1990 and to evaluate alternative means of satisfying these requirements. Figure 2 shows the major research activities. A system of models is being developed to forecast demand for passenger and freight transportation based on projected levels of population and economic activity. Location and activity mix is to be determined by three procedures: changes in land use based on extrapolation of trends, changes in land use and location attributable to the introduction of new transportation facilities and services (inputs), and changes in location and land use attributable to other public policies.

Demand will then be assigned to regional transportation networks to determine capacity re-

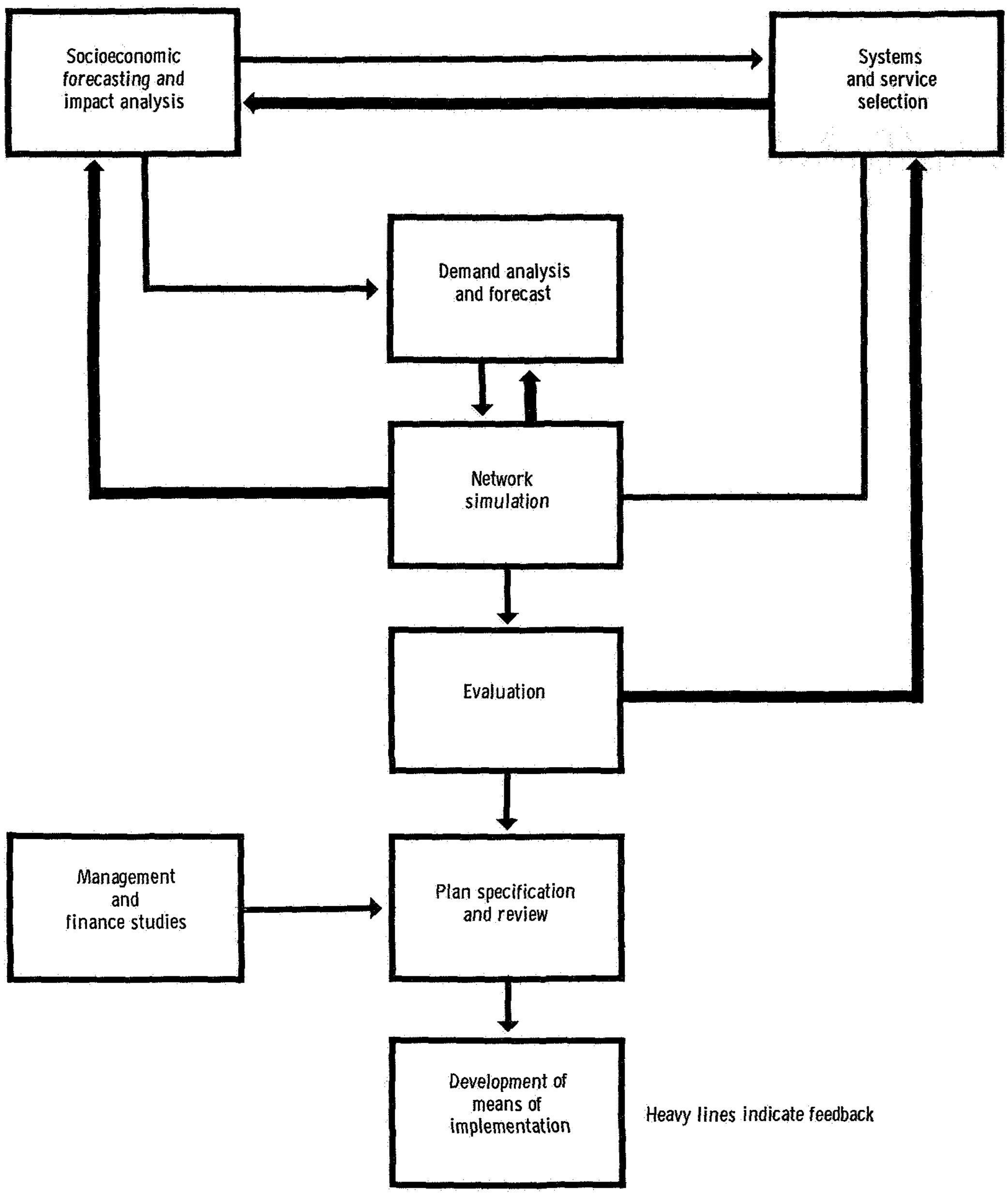

FIGURE 2.—Major research activities of the Northeast Corridor Transportation Project.

quirements for various types of services or various links of the network. Simulation of network operations will produce most of the inputs required for evaluation.

The system of models is designed to operate recursively. Recursion permits the incorporation of locational changes attributable to changes in transportation network operation into the demand forecasts for the succeeding time period.

Conceptually, the focus of analysis and planning lies in the design of the network. The network is conceived as consisting of sets of services between nodes representing geographic areas. In other words, the network is defined in terms of the output produced by the operation of facilities and vehicles. The design of regional transportation networks is the principal concern of the activities designated as systems and service selection in figure 2.

It is through the design of networks that: the operation of new transportation technologies can be tested, a variety of policy objectives concerning regional and subregional development can be evaluated, and market generated demand can be satisfied. Consequently, the tasks related to the development of alternate transportation networks for testing and evaluation are among the most critical in the approach to transportation planning used by the Northeast Corridor Project.

The planned transportation network is, in effect, the tangible manifestation of policy objectives to be attained and demand generated requirements to be satisfied. The elements of network design include increased capacity to accommodate expected growth in demand, changes in accessibility, connectivity, pricing, service frequency, and demand responsiveness. Network design is the final step in a sequential process that begins with postulating alternative regional goals in the broadest terms, e.g., rates of growth, patterns of spatial distribution, and activity and land-use mix. Through a sequence of steps, these goals are then made increasingly specific until a network design can be derived from the process. Ideally, the search and choice process referred to above is one that is based on multiple interactions between steps and successive evaluation and elimination of some of the options.

Clearly, the single most significant constraint in the process of devising alternative networks for the future is the existing network. Even though the network for a region such as the Northeast Corridor may be far from the ultimate in effectiveness, it is a highly articulated set of transportation linkages representing an investment of billions of dollars. Moreover, it is not tenable to assume that these facilities will simply be abandoned. Thus the project staff must assume that within the 25-year period that represents the planning horizon of the project, the largest portion (measured in miles or structures) of the future network will consist of the existing facilities. It follows that the network design activity must include a substantial share of attention devoted to improving the efficiency of these elements as well as to interfaces between these and new facilities.

The output of the alternatives development activity consists then of a limited set of networks and specifications for the staging of the introduction of the elements. These should be representative of the full set of options open to the policymakers.

The new networks are coded into the network simulator, either as new links or as changes in the parameters defining operation of a particular link. The forecasted demand can then be unified to the network, capacity requirements determined, and other adjustments to the network design made.

Some evaluation is to be incorporated into the process of developing alternatives, to reduce the very large number of possible alternatives to a manageable set. Another contemplated step in evaluation prior to simulation would involve the application of criteria of effectiveness to the multimode transportation network designs. In the light of these criteria, a particular network design subject to a particular set of constraints would be optimized. The problems of developing such criteria are currently being examined.

Evaluation of the outputs of the network simulation is to be done in the framework of an accounting system. The first category includes relatively traditional benefit-cost methods and represents both the user's and operator's point of view. The second category is that of impacts or indirect effects in which changes in location resulting from changes in the network will be evaluated. Under this heading, an attempt is being made to analyze and evaluate change in interregional comparative advantage attributable to improvements in the transportation network. The third category of evaluation is a qualitative one. Under this heading, the consequences of various types of network design will be compared with a number of possible spatial orderings of land use and activity patterns in the region.

This framework of evaluation does not lead to a single ranking of alternatives. Rather it leaves to the policymaker the final judgment about the relative significance of these categories in relation to each other.

The Northeast Corridor Project is currently past the midpoint of its contemplated study period. As indicated earlier, many of the techniques interpreted into the design of the project have to be developed again. Even if the effort does not prove successful in all its aspirations, the project is significant because it is the first in which a systems analysis approach has been used to plan transportation networks on this scale.

Other Large Regional Studies

The problem of urbanization on a regional scale with its attendant consequences, though farthest advanced in the Northeast, is by no means unique to that region. Several such studies are currently under discussion, and planning for one such study has been completed in California. In 1965, the state awarded North American Aviation a contract to prepare a plan for performance of the California Integrated Transporation Study.

Supplementing state funds with corporate funds, North American put together a sizable systems team and completed its assignment in approximately 6 months. The NAA effort is in many respects similar to the Northeast Corridor approach as figure 3 indicates. Both studies contemplate moving toward objectives stated in developmental economic and social terms. Both expect to recommend the introduction of new transportation technology where analysis shows this to be cost effective.

Perhaps the major difference in the two study plans is in the treatment of the planning process. The California approach visualizes a rather well developed statement of objectives to be furnished by state officials. The Northeast Corridor approach postulates that the planners will develop an initial set of alternatives to indicate to the policymakers the range of options open to them.

The Transfer of Systems Analysis Techniques

During the last several decades, transportation planners have been developing their own set of systems analysis tools, many of which are similar to techniques developed with NASA funding. Simulation models in particular have been used with some success for transportation systems. Some of the other techniques applied in NASA-funded programs show potential for use in transportation planning.

The general techniques of statistical decision theory can be used as a framework to structure the choices between alternative systems in transportation. These techniques are particularly well suited for use in transportation because they allow the planner to explicitly consider the time variable. The sequential character of the decisions that are made can be modeled, and their interrelationships studied. The use of statistical decision theory in a large regional planning system leads to a large complex decision model. A decision model of similar dimensions was constructed to analyze the planning of the Voyager program (see Application of Decision Analysis to complex Program Strategies in ch. IV). The techniques used to develop and analyze this model could be transferred to the transportation planning models.

The transportation systems for a given region form a redundant network of routes and means for traveling between different locations. The redundancy analysis described in chapter IV is a new method for optimizing this type of system. Essentially the technique would designate a "baseline" system necessary for transportation between all important locations. Then, additional redundant routes and modes of transportation would be added until the most cost-effective combination of the redundancies was determined. The total system represented by a baseline network and the redundant routes would be the "optimal" transportation network. The reader is referred to Mission Optimization Via the Selection of Redundancy in chapter IV for a more complete description of this technique.

The cost-estimating systems developed with the aid of NASA funding are the type of techniques required for large complex systems. A good example of this type of technique is provided in The Manned Spacecraft Cost Model in chapter IV. The techniques are usually based upon the concept of a library of Cost-Estimating Relationships which express the cost of each system element as a function of the performance which will be required of it. This same type of constant and systematic cost-estimating model could be used in planning the nation's transportation systems.

Finally, the use of large complex data-gathering systems is necessary to maintain current estimates of the flow of different forms of transportation. Forecasts of future flows must be derived from this data. NASA has developed a complete management information system which collects, processes, and forecasts time-series of data. This data and information system is described in FAME in chapter IV. The system has

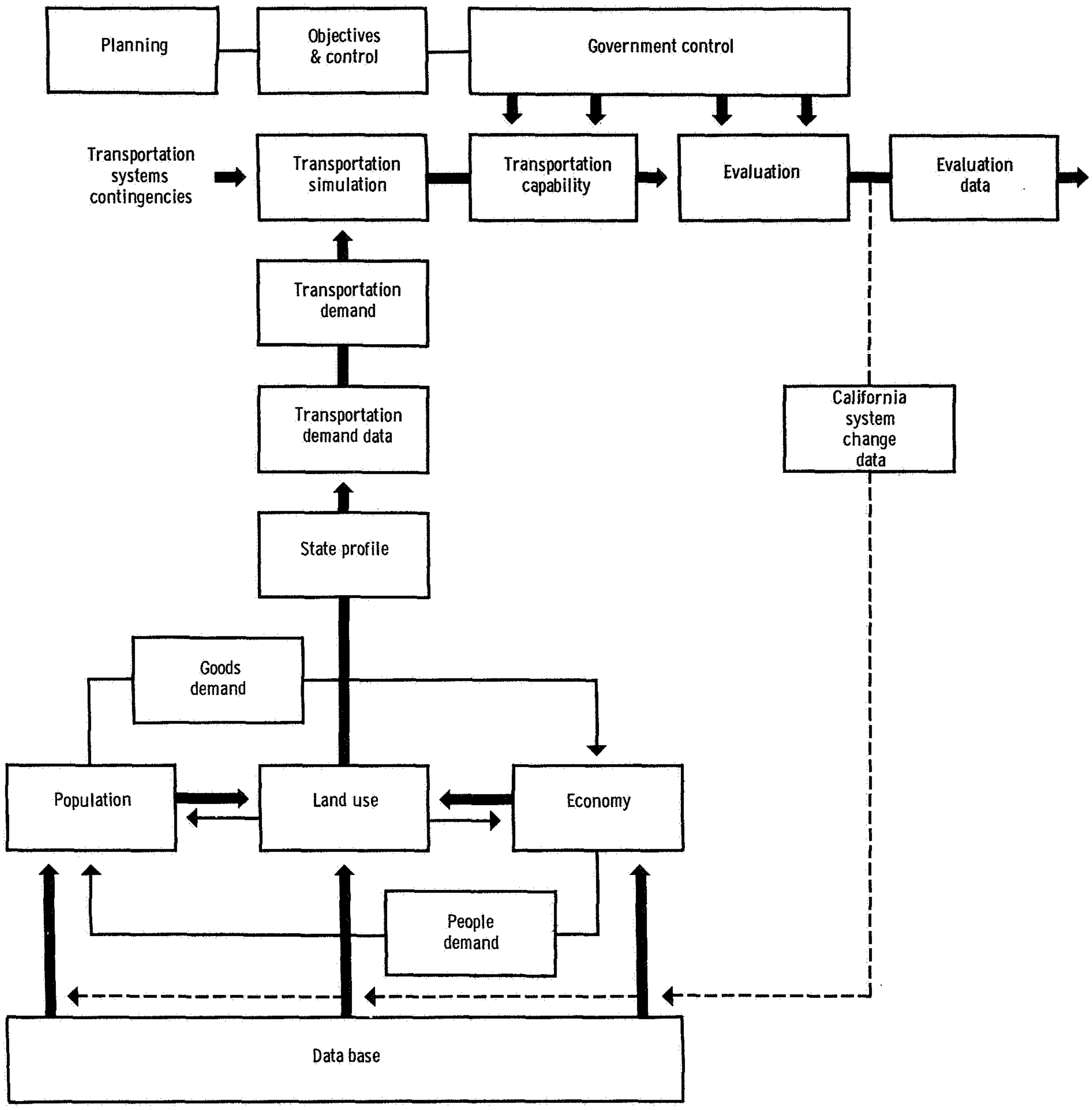

FIGURE 3.—The California model.

the additional capability to automatically assess the "criticality" of any data which fall outside a set of designated control limits.

A Note on the Problem of Objectives

This brief and far from comprehensive review of some of the applications of systems analysis to transportation problems indicates that the principal applications of these techniques tend to be to planning problems, both in the formulation of specific area problems and in the resource allocation process. The definition of objectives in this context is a problem of great significance and difficulty.

In many hardware applications of systems techniques, objectives can be specified relatively unambiguously. This is rarely true with the class of public sector problems which includes transportation. Transportation is a means to an end, not an end in itself. Improvements in a transportation system tend to serve broad social and economic ends about which there may be little concensus. Moreover, the impacts of changes in transportation services are discernible both in macroeconomic terms, e.g., as a factor in the rate of gross national product growth, and in micoreconomic terms, e.g., in the dislocations caused when a highway is constructed through a neighborhood. There is generally no single clean-cut decision criteria for transportation planning and programs. Even when there is, a great complex of potential veto groups must be dealt with, and the relevant policymakers do not always have a clear understanding of the full range of options available to them.

Some sovereignties may provide well articulated goal statements. Those who developed the plan for the California Integrated Transportation Study confidently expect that the state government will provide such a statement of goals. However, in many instances, this type of goal specification cannot really be expected. In consequence, the systems analysis framework must be adapted to the conditions under which most transportation related analysis and planning takes place.

Most of the basic systems procedures, specification of systems boundaries, specification of major variables and their interactions, etc., remain unchanged. However, the concept of alternatives must be broadened to include not only means but ends. The systems approach is then incorporated into an evolutionary planning analysis process in which alternative objectives are evaluated together with alternative means of attaining them. This process is based on the assumption that the planner will inform the policy maker of his options, and that a set of objectives and programs directed toward these objectives will grow out of the interaction between the analyst and the policymaker.

The Use of Systems Techniques in City Administration

The City as a Functional Unit

The officials of every city are subject to a set of demands from the population in their jurisdiction. In general, two types of demands impinge on city officials: demands for the continuance and improvement of existing city operations, and demands for the development of new projects. The distinction between operations and projects is important, for the problems encountered in the management of the two types of activities are markedly different.

Another type of input into a city administration, which may be called supports, provides the funds for the direction of operations and projects. Included in this category of inputs are city tax revenues and state and federal financial assistance. The function of a city administration is to allocate these supporting inputs to the various operations and projects to satisfy the demands of the people. The conversion of supporting inputs into programs to meet the city's needs involves several different functions. These functions of the city administration are to:

(1) Perceive the demands
(2) Forecast available supports
(3) Develop meaningful decision criteria which allocate the support to the most pressing demand

An adequate data system allows a city administration to estimate better the manpower and budget requirements of both its current and its possible future activities. An ability to estimate future costs, when combined with techniques for gaging public and governmental support for alternative programs, gives to a city a long-range planning capability that can result in a more efficient administrative operation. It allows officials to gain an overview of the city's activities by showing how different programs complement each other.

The model structure suggested is illustrated in figure 4a. The extent to which an administration's decision meets the constraints of public demands and the availability of funds is a function of the administration's ability to perceive correctly the types and intensity of the public's demands, and to locate and apply its supporting inputs to these demands. Thus the performance of an administration can be influenced by its decisionmaking criteria and the application of techniques which permit an adequate reading of both demands and supports, thereby allowing the city to find a cost-effective approach to the solution of its problems.

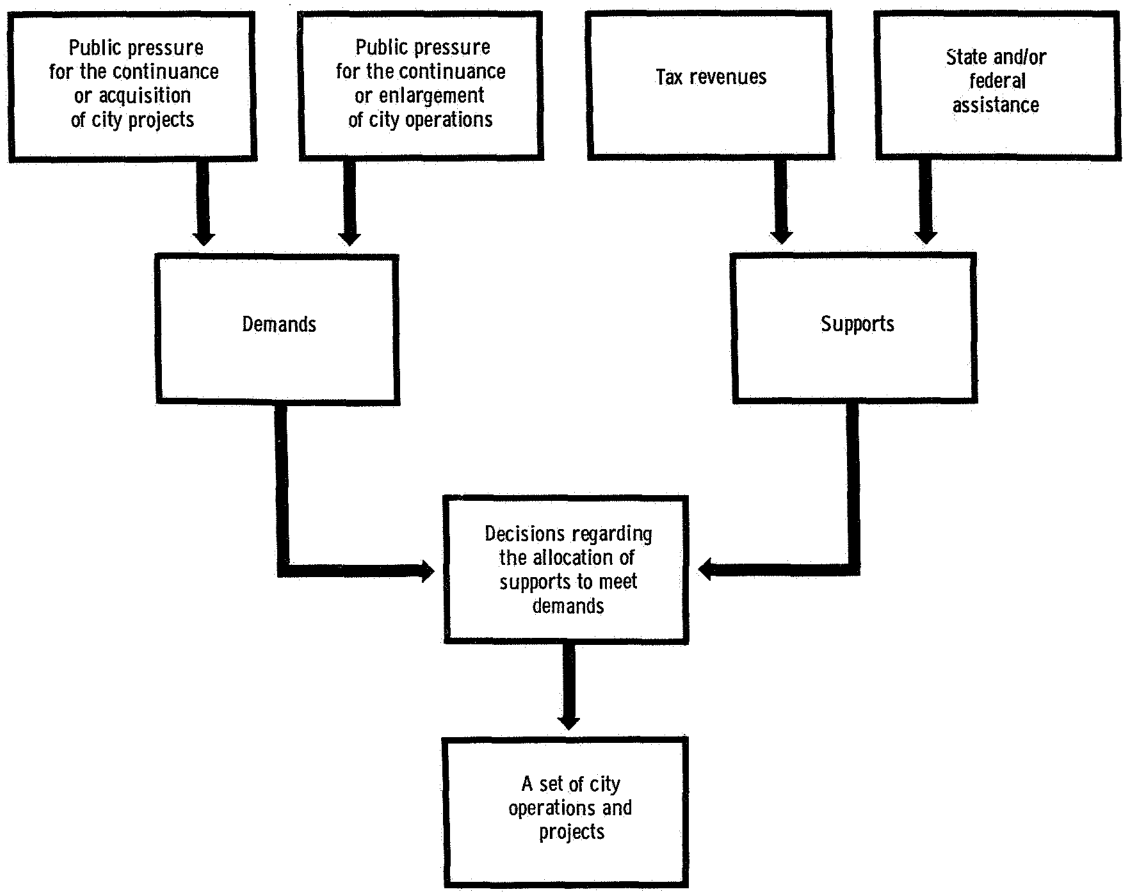

FIGURE 4.—A functional model of the city.

The Potential Applications of Systems Technology

The complex set of interrelationships with which city officials must contend indicates the need for them to perceive their jurisdiction in a system and to recognize the possible consequences of their decisions. Training in these abilities could be aided by use of a gaming simulation similar to the management exercise developed by NASA and described in GREMEX in chapter IV. Officials could be involved in the simulation of city programs and could be asked to reach decisions on both the content and management of these programs. These decisions could then serve as the basis for determining the extent to which the officials reached a preprogrammed set of time, cost, and performance criteria. This type of training simulation would be applicable when an overall objective, e.g., an air pollution program, had been established, and when appropriate performance criteria had been developed. Simulation is particularly appropriate when the teaching objective is training in the management of programs for which funds have already been allocated.

A number of other NASA studies have potential application for existing programs. Since many projects can be designed and managed in different ways, techniques which allow the comparison of alternative methods of operation may point out the most cost-effective approach. The techniques of statistical decision theory can be used in this comparison. These techniques yield a structural framework from which cost-benefit analyses of different program strategies may proceed. An example of the use of these techniques in planning space program strategies is described in Application of Decision Analysis to Complex Program Strategies in chapter IV.

The FAME methodology is a data-handling

and analysis system which could be used to evaluate the performance of a city's air pollution control, public transportation system, health program, and a number of other publicly operated programs. In each instance, the successful application of a FAME system would rest upon the collection of relevant statistics. These statistics might be pollution data, user rates for a transportation system, or health records. Since each of these programs represents a portion of the city's budget, a FAME system could be used to increase the effectiveness of the overall administration's budgetary control process.

Certain specialized problems involved in the management of police and fire protection systems deserve special comment. One of the foremost problems is the scheduling of available personnel. The scheduling problems for a large urban police force are so complicated that systems techniques should be used to perform cost-benefit analyses of different scheduling strategies. The effects of different assignments of men should be determined. These problems can be attacked with simulation techniques similar to the one developed for NASA to study the scheduling problems on manned spacecraft. This type of simulation technique allows the user to study concurrently the facilities design, resource allocation, and scheduling problems which arise from the man-machine interaction. The simulation technique can also be used to simulate various uncertain events and their effect upon the standard scheduling procedures. For example, not only the normal crime incidence but a large urban riot could be simulated; and the ability of the personnel scheduling system to adjust to this riot could be studied. In general, the techniques of man-machine-environment simulation can provide a convenient framework for analyzing scheduling procedures.

The design of adequate police and fire protection really amounts to the design of the redundant facilities needed to safeguard a community. Most of the time firefighting equipment lies idle. Only on rare occasions is the full complement of a community's firefighting equipment used at the same time. The techniques of redundancy analysis developed with the aid of NASA funding may be helpful in analyzing the design for the system's facilities. These techniques can produce cost-benefit analyses of the contribution of each additional facility or group of personnel to the overall objective of safeguarding lives and property.

The police department of a large urban area has a particularly acute need for an efficient data-handling and information system. Furthermore, it would be helpful if this information system could be used to predict the incidence of crime and traffic accidents across the city. A management information system developed by NASA for collecting and forecasting data is described in FAME in chapter IV. An adaptation of this data-handling and forecasting system could be used to monitor and evaluate crime statistics. The crime statistics could be segmented by type of crime and geographic region. A historical time-series of data could then be collected and regularly updated. This data could be automatically analyzed for historical trends, and the trends could be projected into the future to forecast crime patterns across the city. These forecasts could provide a rational basis for the resource allocation and scheduling problems faced by large urban police departments.

The applications of aerospace technology discussed thus far have all been directed toward currently existing city operations. At any given time, an administration also may be involved in negotiations with the federal or state government for funds to initiate a new project or to alter an existing project. This is the second type of "demand" illustrated by the model in figure 4. The members of an administration may also disagree about the desirability of starting or revising projects. Since the outcome of such negotiations and debates is uncertain, the city must estimate future expenditures and manpower requirements without knowing if or when certain projects will be included in the city's activities. The long-range probabilistic planning techniques developed with the aid of NASA funding can provide a means for estimating those resource requirements for project-oriented activities.

These long-range probabilistic planning techniques could be applied by compiling a list of all potential city projects. For each of the possible projects, subjective probabilities would be used to estimate the probability that it will be undertaken; and secondly, probability distributions of potential starting dates would be formed. This data, when combined with estimates of a specific project's manpower and resource requirements, can provide a city administration with information on expected future operating costs for each project. Once these calculations have been performed for each potential project, the data can be collapsed into a master matrix to display the city's budget and manpower requirements as a function of time.

The techniques for long-range planning are particularly valuable in that they can be used as a means of coordinating the administration's efforts to obtain additional funding. The master matrix indicates expected variations in the city's future budgetary requirements. By looking at these variations, city officials may find that if they continue to seek the acquisition of a certain set of projects, they may not be able to realize either the manpower or resources required during a particular future time period. This knowledge could serve as the basis for a rescheduling of the city's project acquisition efforts, thereby preventing future budget deficits. By forming a master matrix that would chart the city's personnel requirements as a function of time, officials would have a basis for forming hiring, training, and termination schedules and for estimating future budgetary requirements. The appearance of severe budgetary fluctuations might indicate that a rephasing of the city's programs would be advisable, in that it may then be easier to match available funds to budgetary requirements. This may have the effect of reducing the need for borrowing, resulting in a more cost-effective management of the city's programs.

Potential Applications to Public Health Programs

Introduction

Many recent trends point to the need for a systematic approach to public health programs. Medical costs, concern over medical manpower shortages, the inception of new and comprehensive programs in health planning, and the establishment of new methods for health care delivery all indicate potential for the application of systems technology. This section will describe several important public health problems and systems techniques that may be valuable in meeting the needs.

Health Care Planning and Resource Allocation

Area-wide health planning is concerned with the allocation of scarce resources among competing projects. Systems techniques can aid in this allocation process. For example a system such as NASA's long-range probabilistic planning model can be used to estimate personnel and capital resource requirements for a number of projects over time. Public health projects must be related directly to the supply and demand for all skill levels of medical personnel, and to the availability of such equipment as cobalt units, expensive patient monitoring devices, etc. The long-range probabilistic planning techniques could be used to estimate these resource requirements in health planning. Topics such as the much-discussed regional distribution of physicians or resource competition between adjacent facilities could be treated by these techniques. If applied on a national program level, this approach would produce economically valid measures of manpower "shortages" in many areas, putting discussion of manpower "needs" on a firm basis.

Public health programs have a clearly defined "mission," the saving of human life. A mission optimization technique developed with NASA funding, which assesses the cost effectiveness of additional, redundant systems in achieving mission success, might be adapted for several health applications. Hospital planners might be able to use a similar device to determine the optimal instrumentation of an intensive care unit or an operating room. Where area-wide capital equipment planning is possible, the optimization technique might help to avoid uneconomic duplication of high-cost, low-utilization facilities.

Pilot Programs in Medical Care Delivery

Until recently, the specific tasks assigned to various members of teams delivering health services were rather rigidly defined. The focus of attention was on the short-term general hospital, subdivided into its various wards and services. Today, however, shortages and needs have given rise to experimentation with whole new systems of medical care delivery. Neighborhood health centers (under the Office of Economic Opportunity) provide care in urban ghetto areas and often act as satellites to community hospitals.

These centers may train and utilize disadvantaged neighborhood residents as part of the health team, redefining their job categories. Enlarged hospital outpatient departments are rapidly changing the role of the community hospital and imposing new demands on the hospital's resource structure. To plan the introduction of these new care delivery concepts, health planners need a technique for modeling their functions in order to predict the resource utilization and cost patterns.

Simulation techniques similar to NASA's space station simulation model could be used to study these new systems. Dealing with inputs of health worker skills, care delivery tasks, and alternate capital resource structures, the model might:

(1) Suggest the most economical patterns of manpower utilization within a given facility, allowing the greatest possible division and specialization of labor

(2) Schedule facility operations, adjusting services to changes in patient demand

(3) Estimate care delivery system costs and provide a means for cost-effectiveness comparisons of alternate systems (provided that problems of quality control in health care can be overcome)

(4) Specify alternate system demands on stocks of various scarce resources, such as hospital beds

Simulation techniques should be helpful in some or all of these problem areas. The space station simulation model is particularly useful for the optimization and scheduling of manpower intensive functions such as these public health centers.

Data Acquisition and Control

The current emphasis on local and area-wide health planning has widened recognition of the need for operational public health data systems. NASA's data-handling and information system called FAME may have potential for utilization in this field. It is a management control system for reporting, analyzing, and forecasting operational data on critical program areas. The system automatically indicates to the administrator the criticality of various statistical trends describing program functions, and can be used to outline the alternatives open to him to reduce this criticality.

For example, if data were available on the supply and demand for various categories of medical and paramedical manpower in a given geographic region, the FAME system could predict shortages and oversupplies of various skills for the medical facilities within the area. FAME could automatically process this data and present the regional health planner with indications of the degree of criticality of these shortages and/or oversupplies. On the basis of this knowledge, decisionmakers could more quickly move to correct the supply and demand balance by:

(1) Increasing the outputs of various manpower training programs (such as graduation from nurses' "refresher" training or medical schools)

(2) Redefining certain jobs for which labor shortages existed, to utilize oversupplies from other occupational areas

(3) Promoting interarea or interregional mobility of available manpower to locations of labor shortages

FAME could perform essentially the same function with respect to the occupancy or utilization rates of medical facilities in an area, contributing solutions to local problems of peak and off-peak utilization differentials and apportioning patient demand between facilities according to available supply. FAME could also monitor the construction of new medical facilities, adjusting bed capacity, for example, to revealed trends in the needs.

Objective Formulation and Decision Analysis

Attempts to apply cost-effectiveness or planning, programing and budgeting (PPB) techniques to the health field are currently experiencing a common difficulty: inability to achieve an adequate definition and interrelation of the objectives of health programs. NASA's mission success evaluation technique could help to structure this problem by providing a means by which a vast array of program goals (many of them highly subjective) could be classified and codified into a hierarchy of interrelated objectives.

If adapted to the health field, this technique would accept the judgments of health planners on the importance of the objectives attained by any given health program with respect to overall health goals. Postprogram judgments of program success could be used to generate performance indices for each program component. This technique would also enable the planner to construct mathematical models which, on the basis of past program performance, would indicate the probability of future program success in a given area. The values generated by this technique would have no greater claim to validity than any other judgments, but their systematic interrelation could aid in specifying the effectiveness of any program mix.

The mission success evaluation tehnique could, for example, be used to relate systematically the contributions of air and water pollution control programs, rat control programs, or programs training public health nurses for their mission of improving environmental health. Or it could be used to compare the effectiveness over time of a series of projects directed toward closely related goals.

Another systems analysis technique which could be useful in the health area is statistical decision theory. This technique defines a series of strategic program decisions which must be made, allows the planner to assign subjective probability assessments to various unknown events, and yields cost-benefit comparisons of alternate program configurations

In the public health area, relatively large capital expenditures must be made with a payoff period far in the future. Changes in technology, morbidity, or the demographic profile of the population may vastly alter optimal health system choices. Thus if the planner could set probable values on these uncertain events, he could quickly compare alternative current investments in the light of possible future events. Such an analysis could also encompass additional strategic uncertainties, such as:

(1) The availability of certain scarce resources

(2) The degree of political support or community participation obtained for a given program

(3) The interrelationships between the given program and other health programs operating at the time of its introduction

Statistical decision theory techniques can be adapted for the evaluation of public health programs even where there are large uncertainties in the program environment. These techniques allow the decisionmaker to structure these uncertainties into a consistent and systematic analysis which forms the framework for the necessary cost-effectiveness studies.

Potential Applications to Social Welfare Programs

Objective Formulation and Comparison

Although general agreement can be obtained on such social welfare goals as "an adequate standard of living for all Americans" and "the availability of employment opportunities for all qualified workers," agreement on concise operational objectives for social welfare programs is extremely difficult. Welfare goals are related to and derived from the individual and social values of those who set them and frequently change. Often as a direct result of changes in the political and social temper of the electorate, a program's operating structure may undergo abrupt changes. Program emphasis can be shifted by administrators or by the public without regard to the interrelationships of program objectives.

To stabilize the purposes and forms of welfare programs, it would be helpful to have a technique for establishing classified and codified hierarchies of interrelated objectives for multiobjective programs. Such a technique could form the first logical step in the construction of a true cost-benefit analysis. With the aid of NASA funds, this was attempted for a space mission series. As programs of manpower development and training, work experience, youth education and training, and employment-related services multiply, their interdependencies become more pervasive. If the contribution of each program to an overall welfare-maintenance goal (or its subgoals) could be specified, several key performance indices for each program could be employed in program evaluation and modification decisions.

Today efforts are being made simply to identify the range of relevant social welfare programs serving given target populations and to classify the outputs. Obviously, social science cannot yet specify the precise, quantitative interrelationships. Nevertheless, agreement on the specification of a subjective value structure could be valuable and might form the basis for more objectively determined systems. Such a value structure would form the core of a Planning, Programing, and Budgeting System (PPBS) in the social welfare program area.

Data Control and Evaluation

Recent social research has isolated sets of sociodemographic population characteristics linked to the prevalence of poverty within certain population groups. Research on "employment multipliers" has made it possible to predict interindustry changes in employment on the basis of single industry employment trends. It is both important and necessary to have data which describes the birth rates, or family-formation rates within various socioeconomic groups and other demographic data so that we may predict changes in levels of effort for social welfare programs.

Even though in many cases the data necessary for program control are not available, much can be done to systematize the control of existing data and to make the data more useful to local administrators. FAME (see ch. IV) might be adapted for such use. To determine the criticality of existing manpower shortages in various areas, FAME could be modified to accept monthly manpower report data and to determine the criticality of marginal employment, supply, or demand changes to the overall labor market balance. The system could then compute input or output changes necessary to meet shortages or oversupplies and report such findings to local manpower program administrators.

Data on population migration; rates, lengths, and recidivism of unemployment; family composition; and characteristics of the labor market could be processed by a FAME-like system for public welfare programs. Program administrators could be alerted to changes in caseloads and to the desirability of initiating programs (such as child day care) which might reduce the criticality of case overloads.

Once a causal relationship between poverty characteristics (family status, educational level, race, place of residence, employment, etc.) and the actual incidence of poverty has been determined, the system could be further used in evaluating the contributions of many unrelated community action activities to an overall reduction of poverty for a target population.

Long-Range Program Planning

Many nationally funded but locally controlled social welfare programs have been handicapped by an initial scarcity of resources (primarily manpower). When many programs compete for the same social workers, administrators, guidance counselors, vocational instructors, and the like, the lack of an overall resource utilization planning structure has resulted in cancellations, payment of overly high wage costs, and last-minute facility changes. National programs sometimes are established without a real understanding of the time sequence of their subsidiary local project developments. A few well-established local projects, for example, may draw and keep skilled staff, thereby monopolizing the resource market. Social welfare programs are subject, however, to sudden surges and recessions of effort. The lack of an overall resource-utilization model for these programs may result, therefore, in haphazard shortage and surplus situations which reinforce each other in severity within geographical or labor market areas.

A long-range probabilistic planning system developed with the aid of NASA funding to solve this type of problem utilizes subjective judgments on program progress to establish time-dependent resource requirements for a series of separate but related individual projects. Assuming that data on manpower supply could be obtained, breakdowns of manpower (including hiring and training costs) by region and program area could be estimated. The same process could be used to estimate the availability and costs of facilities and of special operating equipment, such as vocational education machinery.

Such a system would also indicate the need for the various staff training programs which are beginning for social welfare programs. This system could provide justification for training fellowships, technical assistance between governments, the utilization of private resources where public ones are insufficient, or breakdown of programed tasks into ones which can actually be performed by less skilled (more plentiful) manpower.

Strategies for Program Development

In developing programs such as the Community Action Program, the Concentrated Employment Program, or the Neighborhood Multi-Service Center Program, planners face great uncertainty. Key individuals or organizations may or may not cooperate. The success of a work-training program may depend upon the participation of several private employers and labor unions. The support of many community service agencies may be essential to an effective Community Action Program.

Furthermore, at each stage of program development, the success of new programs may be so dependent upon the initial success of previous programs that the total planning function is complicated by conditional probabilities. For instance, the probability of success for a work-training program for mothers receiving public assistance may be directly related to the prior existence of a program providing day care for their children.

Estimation of a given program outcome on the basis of these many interrelated probabilities and uncertain trends is a highly subjective process. In areas where values tend to differ widely, there is a particular need for planners to specify probable program results objectively, so that program analysis may proceed.

A technique is needed whereby social welfare program planners can:

(1) Define and represent the sequence of decisions which must be made in program development

(2) Identify crucial factors of uncertainty in their program areas, setting some numerical probabilities on certain outcomes

(3) Set values for alternative program configurations and outcomes

(4) Systematically analyze the costs and benefits of alternative programs on the basis of these probabilities and values

The techniques of statistical decision theory are admirably suited for adaptation to these problems. If employed correctly, these techniques should enable one to estimate the costs and benefits of a complex sequence of program decisions, and to compare alternative program strategies.

As social welfare programs become more comprehensive, community based, and dependent upon the participation of diverse interests, the need for such a simplified representation of the strategic planning process increases. Also, as it is found that expensive programs stand or fall on the degree of cooperation obtained from certain individuals or the extent of the coordination developed with other programs, such an analytic device could aid planners in allocating resources in order to change unfavorable odds against certain program developments.

New Departures in the Provision of Social Welfare Services

Several social welfare programs now under development employ new mixes of personnel and equipment in new operating environments. The developers of such new concept programs as a neighborhood multiservice center, a community development corporation to revitalize a ghetto area, or a neighborhood health center, will have to consider operation and scheduling problems carefully.

A possible aid in the solution of these problems may be the simulaton of the entire set of center functions, to obtain schedules and operational procedures on a satisfactory if not optimal basis. A complex simulation technique developed with the aid of NASA funds (see Mathematical Simulation of a Manned Space Mission in ch. IV) is an excellent example of the possible benefits of this kind of approach.

Simulation should help the program planner match the social service tasks to be accomplished by the new program with the skills of available personnel. Staffing and support costs for the program could be computed, and possible trade-offs in terms of resource or manpower quality levels could be indicated.

Such a simulation approach would be particularly valuable where the given program concerned a physical operating site, such as a neighborhood health center, and was a manpower-intensive activity for which the mission and its component tasks were clearly definable. Such an analysis could indicate the potential for utilizing subprofessional workers. Since program operations would be presented in terms of individual tasks, the influence of technological change upon the skill requirements could be ascertained, or attempts could be made to restructure these tasks to fit the capabilities of less skilled workers.

A simulation approach could alleviate the trial and error confusion which usually surrounds the establishment of a radically new social welfare program. It could also provide a model against which to compare the efforts of two or three pilot programs, since by specifying task/manpower allocations it would provide some check on the quality of the services being provided. Hence it could serve as a reference point in a cost-effectiveness analysis. In any case, simulation techniques might be a valuable tool for use in determining broad budgetary and resource requirements for untried programs.

New Applications of Systems Models in Educational Programs

As understanding of the learning process grows, more elements that seem to affect that process are being enumerated. Many of these new elements fall far outside the limits of what were conventionally understood to be educational concerns. The new factors are interrelated in ways that are difficult to measure and analyze with conventional methods. Modeling techniques provide a method for simulating and analyzing complex systems, and several possible applications for these models in educational planning are discussed below.

A mathematical model similar to the models for space station simulation might provide an opportunity to explore the implications of proposed educational environments without costly investment in plant and curriculum materials, staff energy, and student education or miseducation. Several submodels could be employed as components of a large model for computer simulation. One submodel might contain the data base of community and home influences on children; another might contain the preliminary requirements of a program; one might contain the teaching methods employed by the program; one might contain response data to particular methods; one might contain skills to be developed by the program; and one might contain the resources of teachers, classrooms, textbooks, and supplementary materials. By developing a comprehensive model for simulating the many factors affecting students, programs, and administration, data could be acquired that would show how effective programs are at particular grade levels, which groups participating in these programs are likely to profit most, which groups are liable to profit least, and which preliminary requirements must be met if any success can be expected. One might test alternate programs by keeping the following submodels constant: the data base, response data to particular methods, the skills to be developed, and the resources. By changing the teaching methods employed in a given program and the preliminary requirements, one would be able to see which of several alternate programs would have the greatest likelihood of success with a particular group of children.

Without simulation techniques, the effects of proposed programs in an actual school system can be tested in two ways: adding more instruction and services to the system, and/or removing existing instruction and services. To determine the most cost-effective mix of learning influences that are controlled directly by the school system—nature of curriculum, qualities of teachers and books, design and use of classroom, etc.—combinations of these learning influences can be selected for a student body in which nonschool influences have been controlled. The design of the programs depends on *a priori* estimates of the relative cost effectiveness of single variables—a new spelling book, a hot lunch program, a change in student-teacher ratio—information that can be investigated with the use of simple models.

This kind of testing for alternative programs and combinations of programs would be costly and time consuming. Its use would probably be limited to large school systems—such as New York City's—that have a lot of data and a large number of school units. Possible mistakes then could be limited in scope and not weaken the entire system. This kind of experiment would also be well suited for a Federal Educational Planning Agency that would have at its disposal all the resources for conducting the study. The Government could provide incentives for testing the new program through the allocation of federal funds to schools willing to participate in educational experiments.

Data collected by the Coleman Commission while studying the incidence and effects of inequalities in educational opportunity reinforce earlier understandings of the influence of student body characteristics on the level of achievement reached by students. It is becoming clearer that when a student body is composed of students from different socioeconomic levels, and lower level students form a minority within the student body, the achievement of lower socioeconomic level students is positively affected by exposure to students with more money and higher aspirations. Achievement is higher than it would be if the lower level students were in a homogeneous student body or formed a majority of the student population. When students from upper socioeconomic levels are a minority in the student body, there is little or no adverse effect on their achievement level.

This suggests that one way to equalize opportunities is to find different ways of matching students to each other. The problem is complicated by the fact that socioeconomic divisions are often racial and urban-suburban. Optimizing the mix of upper and lower level students in our schools is not as simple as rearranging a stable and passive population. In fact, the population distribution has been becoming more and more unbalanced. Center city populations have been increasingly composed of lower level families who also belong to racial minorities.

Since there is not a heterogeneous mixture of socioeconomic groups feeding into small neighborhood schools, neighborhoods that the schools draw on might be redefined. This can be done by—

(1) Redrawing school districts around existing schools
(2) Strategically locating new schools
(3) Transporting inner-city students across the old neighborhoods to attend upper level suburban schools.

The problem is to determine the optimum mix of student distribution methods, which presupposes an understanding of the cost effectiveness of the various methods and what mixture of students from different economic levels yields the most student achievement. We should also analyze which agencies—local, state, or federal—can be most effectively responsible for such a program, and investigate the costs of these programs. The experience and techniques NASA has acquired in optimizing complex operating systems might be usefully transferred to this distribution problem and similar problems in educational planning.

The number of variables affecting given educational programs is enormous, and all these variables have some impact on the individual student and affect his response to the learning environment. It is difficult, then, to measure the success of a whole educational system for one student and even more difficult to measure the success of education for many students. To gain any useful information about educational systems, however, it is necessary to make both qualitative and quantitative distinctions.

Testing is the traditional method used, but too often the limitations of testing are ignored. A test of verbal ability is often assumed to measure intelligence or overall ability when it actually measures neither. Indeed, often the only thing it measures is a given student's ability to take a test. School systems which rely solely on objective testing to measure the success of their programs are doing a disservice both to the programs and to the students. More accurate tests which take into greater account the overall effects of a given program could be devised. These tests could measure not only skills learned and basic knowledge acquired but also the more important changes in motivation and attitude which are results of educational programs and which affect future learning. More accurate predictions could then be made of success or failure for particular student types in particular areas of the curriculum. Once the preliminary data base is developed which can measure motivational and psychological influences in learning, simulation techniques can be more effectively used to predict future successes and failures and to model the educational process.

Finally, systems analysis techniques may be helpful in solving many of the planning and scheduling problems inherent in a large urban school system. Population and demographic data may be compiled and employed in a model which simulates the total future demand for educational facilities. This type of modeling would be a great aid in long-range planning for educational systems. Schools could be located optimally with respect to observed and predicted population trends. The requirements for teachers and supporting staff could also be estimated years in advance. Furthermore, simulation and scheduling techniques could be used to accomplish the yearly allocation of students and teachers to the available facilities. The more mundane problems of class scheduling in a given school could be approached with the use of systems techniques. Although the simulation and scheduling techniques developed with the aid of NASA funding may not be directly applicable to these problems in educational systems, they provide examples of the general kinds of techniques that must be developed for systematic educational planning.

CHAPTER IV

A Review Of Selected Systems Analysis Techniques Developed With NASA Funding

APPLICATION OF DECISION ANALYSIS TO COMPLEX PROGRAM STRATEGIES

The methods of decision analysis have slowly become more familiar tools in decisionmaking as people have seen that uncertainties and subjective evaluations can be dealt with quantitatively and logically. Aided partly by funding from the Jet Propulsion Laboratory, the General Electric Co. applied these techniques to developing an optimal strategy for Martian exploration. Reference 3 describes this use of the concepts and techniques of decision analysis to aid in determining the best series of spacecraft configurations for missions to Mars in the 1970's.

Basic Tools of Decision Analysis

A decision can be defined as a particular action chosen among alternative actions. Note that a decision is not merely a passive choice, but action based upon that choice. A policy is a set of sequential decisions made on the basis of intermediate outcomes.

A decision tree is a graphical method of displaying choices and alternatives with their associated values, costs, and uncertainties. It shows both the interrelationship between the decisionmaker's choices and ordering between outcomes and points of decision. A sample decision tree is shown in figure 5. It has two types of nodes.

(1) The decision node (signified by a large X) indicates the point where the decisionmaker must choose between several ways of allocating resources. Each branch (called alternative branch) leaving a decision node represents one of the alternatives available.

(2) The chance node or "nature's decision" node indicates those points where the process is subject to events beyond the decisionmaking control. Each outcome branch emanating from the chance node represents one of the possible outcomes which may occur at this point. Probabilities of occurrence and values are assigned to each of these outcomes.

Utility Theory

We often face the problem of having preferences between objects and situations without any convenient quantitative mechanism for conveying our preferences to others. Utility theory provides a framework for quantifying preferences. Once a "utility function" has been established for an individual, his choices between various alternatives can be predicted without his presence, both in risk-free and "gambling" situations. Utility theory is based upon a set of axioms on consistency requirements that one would expect logical preference functions to follow. Von Neumann and Morgenstern showed that if a utility function which is consistent with the axioms exists, and if a decisionmaker selects choices which maximize the expected value of this utility function, then the choices will be consistent with his tastes. (The expected value of a variable is defined as the sum of the products of the value that the variable may have times the probability that the variable actually takes on that value.)

To illustrate this concept by an example: Suppose we are given the option of playing one of two games of lotteries. A lottery is a gamble where the prizes are known and the probabilities

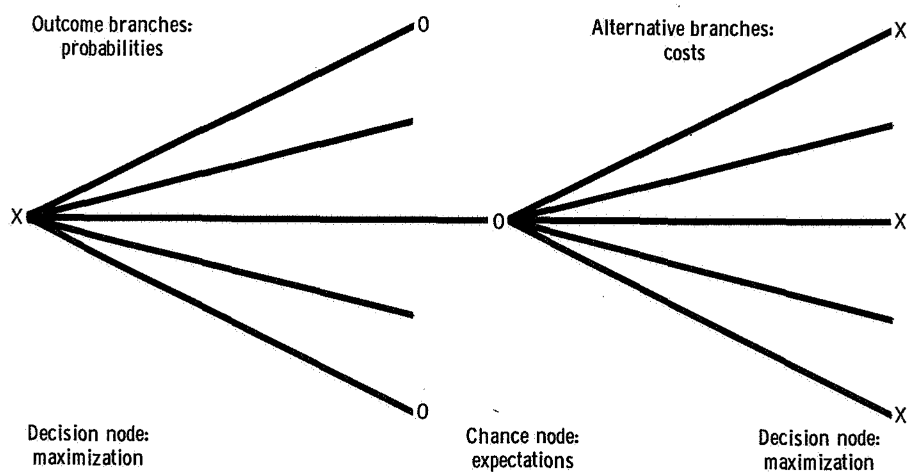

FIGURE 5.—Decision tree relationships.

of attaining the prizes are known. Lottery I will yield A with probability P_I and B with probability $1 - P_I$. Lottery II will yield C with a probability P_{II} and D with probability $1 - P_{II}$ (see fig. 6). We shall assume that we have somehow determined our utility for the prizes: $U(A)$, $U(B)$, $U(C)$, $U(D)$.

Then, U(I) is the expected value of the utility of lottery I. According to the theory, if we were consistent in our preferences, and if we preferred I to II, then U(I) would be greater than U(II). If we preferred II, then U(II) would be greater then U(I). If we were indifferent, then U(I) would equal U(II). It is important to remember that preferences are used to derive a utility function and not vice versa. Once the utility function has been established, however, we can use it in place of the decisionmakers. If a proxy or a computer tried to maximize our expected utility when choosing between alternatives, it would be making choices in accord with our values.

Introduction to the Voyager Problem

The General Electric study, in which Stanford Research Institute participated, was a large step toward aiding planners in making the innumerable decisions necessary in a large-scale program. For simplicity, the methods used on a pilot study of the Voyager mission will be considered. A followup study by the same group handled a more complex set of decisions and alternatives. The following paragraph will describe the pilot study assumptions and constraints.

The Voyager mission to Mars had been approved, and the initial launch was scheduled for 1973. Subsequent to the 1973 launch opportunity, other launch opportunities would occur at regular specified intervals determined by the Earth-Mars geometry. The project manager had already established some constraints on the program. Four available vehicle configurations would be considered with the following functions: C1—a vehicle to perform atmospheric experiments, C2—a vehicle to obtain approach TV pictures, C3—a vehicle to obtain surface TV pictures and perform surface property experiments, and C4—a vehicle to perform life detection experiments. Since the program had definite time constraints, plans and construction for the second launch in the series had to be started before any results were obtained from the first

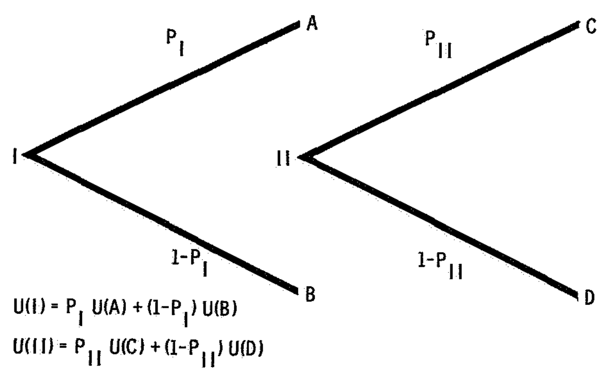

FIGURE 6.—Utility expected value of lotteries.

launch. There was a similar construction lead-time on each of the successive launches.

One might contend that decisions about the configuration of the third or fourth launch might be deferred until more precise information about the vehicle performance was known. Yet in making decisions about the first or second launch, we must consider how later decisions could alter the value of earlier choices. The alternatives, values, and uncertainties of all possible policies must be considered and immediate decisions must be made in accord with the current state of knowledge. As information becomes available in the future, the model may be updated and modified as a subsequent part of the overall policy.

Problem Format

The decision theory modelers set up a general outline for the decision analysis process and then indicated how the Voyager project fit into this structure. Their breakdown of the problem was as follows.

Voyager Pilot Study Outline

A. Pilot problem structure
  1. Decision—which vehicle to use at each launch opportunity.
  2. Alternatives—fly one of the vehicle configurations.
  3. Outcomes—achieve one of four levels of success.
  4. System relationships
     (a) Decision timing
     (b) Value structure
     (c) Cost relationship
     (d) Mission structure

B. Input specifications
  1. Probabilities of outcomes
  2. Values of outcomes
  3. Costs of configurations

C. Outputs
  1. Most economic decision policies
  2. Expected cost of policies
  3. Expected values of policies
  4. Expected value/expected cost
  5. Expected net value of total program

Model Structure

A computer-analyzed decision tree is at the core of this kind of study. The value of each outcome may be given in terms of dollars to make them compatible with cost estimates. If there is a cost associated with choosing an alternative, then before the expected values of the alternatives are calculated, this cost is subtracted from the value of each outcome emanating from the successive chance nodes.

The number of nodes associated with a moderately complex problem is difficult to handle, even with large computers. However, some of the paths in the tree were duplicated a number of times. Consider the following two chains of events: (1) A C1 is launched in the first and second launch periods. Information returns that the first one was a failure. A C2 is launched in the third period. Information returns that the second C1 was successful. (2) C2's are launched in the first two launch periods and we find that the first launch was only a partial success, attaining a level associated with a successful C1. The costs and probabilities involved in reaching these two points are different, but from this point on, all of the alternatives, costs, uncertainties, and values are the same in each case. The modelers use "coalescence" of the nodes; that is, redirect paths to other portions of the tree to eliminate this kind of duplication. They found that in the pilot study this process reduces the size of the decision tree by a factor of 30.

Maximization of the expected net value is often the criterion used for the most economic policy. However, the number of possible policies is huge and the computation of each decision policy may be too costly. The "rollback" technique eliminates many of the nonoptimal policies from explicit consideration. This method consists of making decisions and calculations in reverse chronological order (i.e., from right to left in fig. 5). In this way, when each decision is made, only optimal subsequent policies need be considered.

Three models give the necessary input information to the decision model. They determine probabilities, costs, and values.

The Probability Model

In general, it is quite difficult to get estimates on the probabilities assigned to outcome branches. There are two important reasons for this difficulty. First, the systems associated with a branch are very complex. Engineering data and subjective evaluation are more accurate and more available for elementary systems and operations. The probability model must manipulate this information to produce the branch probabilities. The second problem is associated with obtaining the subjective probability estimates from knowledgeable persons. This is often difficult because of the reluctance of people to commit themselves to these evaluations.

The Cost Model

The cost model estimates the cost of each major resource allocation (i.e., decision). Since the launch systems are somewhat "upward compatible," the construction costs of one of the more sophisticated vehicles is reduced if one or several of the simpler vehicles have been built. Needless to say, there is a considerable saving in cost when a vehicle is duplicated.

The Value Model

Two qualitatively different kinds of values can be associated with the Voyager program outcomes. The first is the direct value of the knowledge obtained. This includes scientific information, such as atmospheric and geological knowledge of Mars, biological data, inhabitability of the planet, etc. The second type of value is that which is the result of obtaining and possessing the knowledge. The effort expended in the program leads to benefits to other space programs and to technological spin-off in other disciplines. Even more intangible, but nevertheless important, are the other rewards: world public opinion, national public opinion, satisfaction of the discoverer instinct, and the pleasure of being first.

It is difficult to sort out these benefits, to evaluate them, and to make sure that they are not "double-counted." Value assignments are not all made by one "man at the top." It is helpful to have a graphic scheme so that the proper evaluations are made by the appropriate people.

To organize the construction of a value function, the modelers subdivided the value components by means of a value tree. Each category of values was divided and subdivided until they were distinguishable products of actual mission functions. It is then possible to estimate what proportion of the total possible value of the program comes from each launch configuration.

Once a tree structure is established, the value of any subsection can be determined by the most knowledgeable persons. For example, a team of scientists could estimate the relative merits between biological and physical experiments. It would be the responsibility of higher officials to determine what proportion of the entire program the scientific experiments deserved.

The Selection of Optimal Policies

The object of decision analysis is to seek out the best policy or set of actions for a system. There is generally no universal "best" policy because one of the important variables in the problem is one's subjective value assignments. When a policy is selected, it does not necessarily constrain the system to follow a unique path on the decision tree, although it does limit the paths which the system might traverse.

Since we are now able to determine the cost and benefit of any path associated with a policy as well as the probability that that particular path will be followed, we can represent each path as a point on a cost-benefit plane. In figure 7 there are three sample policies to consider. Each point represents a path on the tree and has a probability attached to it, given that its associated policy is carried out. Policy 1 has low cost but low benefit. Policy 2 has high cost with low benefit. Policy 3 has high benefit with moderate cost, but there is one point on Policy 3 which has higher cost but lower benefit than some points in Policy 1. We are better off choosing Policy 1 or Policy 3 over Policy 2. But how do we choose between 1 and 3?

"Comparison implies a *single* measure of a policy." We may begin by reducing each policy to a representative pair of numbers: an expected cost and an expected benefit. Figure 8 shows some sample policies represented by their benefit-expected cost pairs. This discussion of optimal decision policies closely follows reference 4. The policies in figure 8 may be separated into three classes:

(1) Totally dominated policies
(2) Marginally dominated policies
(3) Dominant policies

A policy is dominated if there is at least one

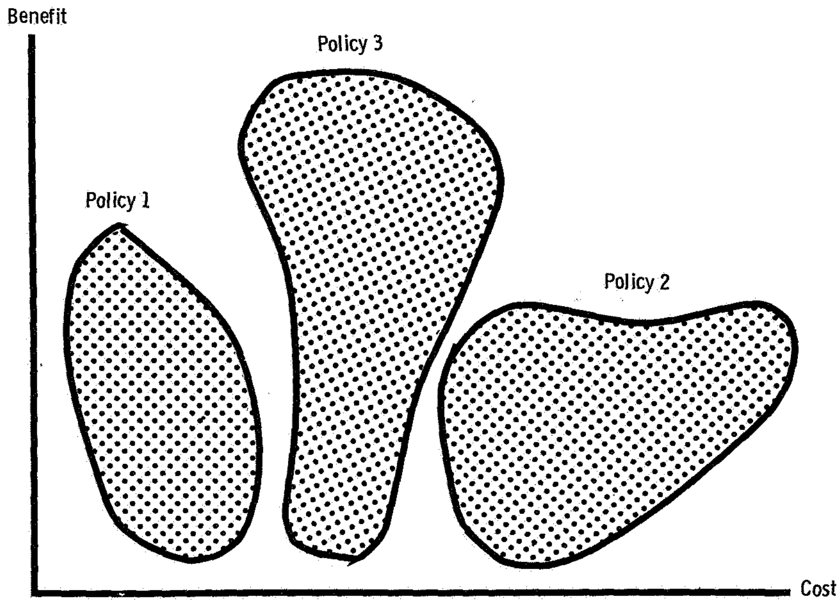

FIGURE 7.—A comparison of decision policies.

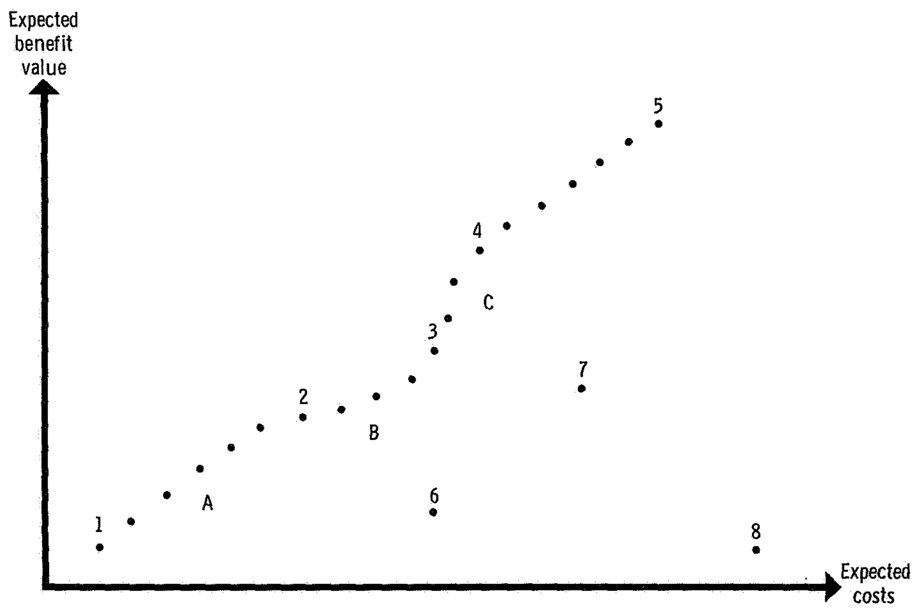

FIGURE 8.—Expected cost-benefit mapping of alternative policies.

policy that has both a lower cost and a higher expected benefit level. Policies 6, 7, and 8 are totally dominated policies. Totally dominated policies can be dropped from further consideration. This simplifies decisionmaking, because the bulk of the possible policies are of this type.

The remaining policies connected by a dotted line in the figure are called envelope policies, and are of two types: marginally dominated policies and dominant policies. Policy 3 is an example of a marginally dominated policy. The slopes of lines *A*, *B*, and *C* . . . show the marginal return from increasing the funding level from 1 to 2, 2 to 3, and from 3 to 4. The marginal return B is less than the marginal return C. This means that increasing the funding from 2 to 3 brings less return per unit cost than the increase in funding from 3 to 4. Since each program is competing for funds with other programs, it would be very unusual to find that directing funds from other programs is worthwhile up to the point 3 but is not worthwhile beyond 3. For this reason marginally dominated policies, such as 3, are eliminated from contention. The remaining policies—1, 2, 4, and 5—are called dominant policies.

One is now left with the choice among the remaining dominant policies. Certainly, one influential factor is the available funds for the program. There is a danger, however, in using the graph in figure 8 if there is a rigidly fixed budget. Remember that the horizontal axis is expected cost, not cost itself. It is very possible that the program cost would exceed the expected cost. There are two methods of handling this problem. The first, and more harsh, method is to eliminate from consideration all policies which have a possible cost exceeding the available funds. The second method is to alter the utility of a policy by adding a "negative benefit" to the existing benefit if the cost exceeds the limiting amount. One might then consider a scheme such as figure 8 with modified expected benefit versus cost.

In a case where funds were not severely limited but nonetheless scarce, one would put money into programs which yielded the greatest marginal return of benefit for cost. Unfortunately, the programs considered during a year are not all presented for inspection at once. Over time, however, the planners will observe that there is a minimum acceptable marginal return under which they may best hold their funds for a more beneficial program later.

Applications of Statistical Decision Analysis

Faced with changing populations, demands, and competitive situations, a businessman must constantly reassess his market position and seek out ways to use ideas and situations to his advantage. These may include designing and developing a new product, expanding existing production facilities, employing different advertising and marketing techniques to different product lines, opening branch offices in potentially profitable locations, or acquiring or merging with another organization. City and government planners similarly must consider possible population shifts, new interest groups, new technology innovations, and changing physical conditions. In both of these problem areas, statistical decision theory can be used as a guide to effective, consistent decisionmaking.

TECHNIQUES FOR SIMULATING AND OPTIMIZING COMPLEX SYSTEMS

Each spacecraft designed and built in support of a space project is a complex system composed of smaller subsystems, assemblies, and components. In manned space missions, the crew becomes an integral part of the spacecraft, further complicating the design problems. The proper design of a spacecraft must consider the whole host of interrelationships and trade-offs which arise from the overall system. The spacecraft must not only perform a certain minimum number of necessary functions, but it must contribute to maximum mission effectiveness for a given cost. Functionally redundant subsystems are included to yield the maximum increase in the probability of mission success. The spacecraft must be designed and the crew must be scheduled to make maximum use of the spacecraft-astronaut combination. These complex design and scheduling problems have been attacked with the aid of several systems analysis techniques. Two of these quantitative techniques will now be described.

The first technique is a complex mathematical model used to simulate a manned orbiting spacecraft. It is an excellent example of a simulation technique that can be used with any manpower-intensive system to improve the design of the system and the scheduling of the manpower. The second technique is a very different type of mathematical model which was developed to aid in designing unmanned spacecraft. The model indicates how redundant components and functions can be added to the design of a spacecraft to maximize the total probability of mission success. This second model also has potential for adaptation and utilization in many different problem areas.

Mathematical Simulation of a Manned Space Mission

A mathematical model to simulate the complex interactions which occur aboard the Manned Orbital Research Laboratory (MORL) was developed for NASA by the Operations Research Division of General Dynamics, and is summarized in a NASA report (ref. 5). The MORL would have a crew of nine men, remain aloft for over 2 years, and conduct over 100 scientific experiments. There is a great need for efficiency in the proper design of such a spacecraft because of the critical weight limits and the crucial need for crew safety.

Many operations and activities are needed to maintain such a spacecraft aloft. Maintenance, experiments, storage and disposal, logistics, and crew duty cycles must all be considered in the design problem. These various activities aboard a spacecraft are not independent, and all possible interactions must be analyzed. Unfortunately, many of these interactions will be far from obvious. For example, if a crewman becomes ill, there are many possible ramifications for the operation of the entire system. His absence from normal duties may affect maintenance or scientific experiments, or both. Clearly, the design, planning, and scheduling of activities for such a space station is a highly complex task which demands a carefully considered set of solutions. For this reason a detailed mathematical model has been developed to simulate the entire spacecraft. The model is programed for a digital computer and makes use of the computer's computational speed.

The mathematical simulation model consists of three separate programs, designed so that each one is an input to the next. The first is called a Preliminary Requirements Model (PRM), which assesses the feasibility of missions, selects crews, and determines skills needed by candidate crewmen. This model develops rough estimates of the missions and screens out any obviously unacceptable mission requirements.

The next program is the planning mode, which deals with such problems as logistics, scheduling, and evaluation. This program schedules the station keeping and personnel requirements, and the experiment requirements, until the manpower resources are used or the experiments completed.

The last program is called the simulation mode, and was developed to determine the effect of contingencies on the mission plan. The effects of various nonstandard spacecraft events are simulated, and the time and duration of the events are generated at random. Such events as system failures, accidents, and meteoroid punctures are generated, and the effects are simulated throughout the entire system including those on payload, crew, logistics, etc.

The problems revolving around the selection and scheduling of the crew are analyzed in all three programs. Thus in the first mode, crews are selected on the basis of skills, crew training, and ability to provide the most effective experimental accomplishments. In the second mode, this preselected crew is scheduled for optimal experimental results. Finally, in the simulation mode the effect of unscheduled events is calculated. The model is developed to handle a crew of up to 24 men.

By scheduling all necessary events into 24-hour units, the three programs permit analysis of resource requirements, expected rate of mission accomplishment, and sensitivity of mission accomplishment to different crew missions and different levels of crew training. The simulation model also permits the determination of the probable deviation of the mission from initial plans. The simulation program can therefore be used as a training aid for potential crews.

A separate program has been developed for mission evaluation. No single measure has been used as a measure of mission value; but a large number of indices were developed which can be presented in various combinations of cost and effectiveness. The effects of different amounts of crew training on experiments, for example, can be evaluated for the effect on the overall mission effectiveness.

The model thus can be used for a wide range of studies involving logistics, crew analysis, resource analysis, comparison between mission plans, logistic failures, and accidents. The model is designed so that selected portions of it can be used for specific studies, a factor which minimizes the computational time and expense. The entire model can be used, however, when it is appropriate to study the behavior of the total system.

This mathematical simulation model is interesting not only because it is an attempt to simulate a very complex manpower-intensive system, but also because it attempts to maximize the output of the system by applying operations analysis. The development of a mathematical model permits much greater flexibility than a physical prototype and is a more efficient and less costly method. Nearly 3 years of orbiting time can be simulated with the mathematical model in about 30 minutes.

Any manpower-intensive system can be modeled with these techniques, and the system design and personnel scheduling problem can be studied concurrently. There will be times when the expenses involved in developing this kind of model are too large compared to the advantages gained. The initial cost effectiveness of this type of model must be studied in each separate case before the development decision is made.

In industry, this type of simulation model can be used to study various work group situations. The working environment on an assembly line may be particularly well suited for an adaptation of this type of study. The design of surrounding facilities can be analyzed in conjunction with the problem of personnel scheduling. This type of simulation approach has the important advantage of considering the system as a whole, with all its interactions. Because of this advantage, the simulation technique may prove superior to the separate and artificially segregated analyses of subproblems within the working environment.

Schools, public health facilities, welfare agencies, police and fire protection units, and other manpower-intensive activities all have the interrelated problems of functional design and personnel scheduling. Simulation models can be developed as a systematic approach to problems in all these areas.

Mission Optimization via the Selection of Redundancy

Another mathematical model was developed to aid in the design of the Voyager spacecraft by indicating the optimal amount of redundancy of components and assemblies. The work was done by General Electric Co. for the Jet Propulsion Laboratory, in connection with the preliminary phases of the Voyager program (ref. 4).

In designing a spacecraft, or any complex system, there are many ways in which the reliability of the system can be increased by adding so-called redundant components. In the design of previous spacecraft, an attempt was made to make the system as reliable as possible, assuming that reliability was synonymous with mission success. Where a mission has many different objectives, this simple identification of reliability and mission success is inadequate. This new approach attempted to place a value on the reliability, and weigh this against the cost of obtaining such reliability, e.g., increased weight. The new approach was an effort to maximize the expected worth of the mission, essentially applying the concept of cost-benefit analysis to the problem. The main features of this technique are described below. The problem was divided into four parts.

First, the mission and the system were defined by means of flow charts, which described the mission from the prelaunch phase until the final landing of an instrument capsule on Mars. The functions of the spacecraft were analyzed in detail and divided into 8000 separate functions. These functions were then related to individual components or specific hardware. Thus the general function "to acquire celestial references" was divided into a number of separate functions, one of which was "to provide coarse sun pointings," and this separate function was then related to a specific piece of hardware; i.e., sun sensor.

A system was then developed which had no redundancy, either of components or functions; that is, a baseline spacecraft design was established with the absolute minimum functions and components necessary to complete the mission. This "baseline design" or "single-string system" was then divided into 59 assemblies or units. Each unit could be made to function by at least two different types of assemblies. The number of possible ways in which different spacecraft systems can be chosen is surprisingly large, on the order of 10^{21} for the Voyager. The problem of choosing the optimal system from among 10^{21} possible systems is formidable. The rest of this second phase was involved with the performance of the hardware, calculating failure rates, and estimating the cost associated with each assembly.

The third phase of the problem solution was to examine and calculate the various possible mission outcomes and to assign worth to each outcome. This was done by first classifying the information that would be received from the spacecraft (the worth of the mission is in information transmitted back) into scientific information or engineering data. Each of these categories of information was then further subdivided and worth was assigned to each subgroup by subjective evaluation. Each subgroup was then correlated with a particular assembly so that the effect of a failure of a component could then be correlated with specific information.

The final phase involved a search through 10^{21} outcomes to select the optimal system. Since it was not possible to examine all the 10^{21} possibilities even with a computer, recourse was made to techniques of dynamic programing which yielded an approximate solution to the problem.

This mission optimization and analysis is particularly interesting because the calculation of the parameters for the cost-benefit analysis involved building a sophisticated set of mathematical models to cope with the extreme complexity and dimensionality of the problem. The ability to model and analyze the redundant functions and components of this complex system is an obvious advantage in solving the problem of spacecraft design. This type of redundancy analysis might also be adapted for use in other areas. The design of ultrasafe automobiles will include redundancy problems, for example, and a cost-benefit analysis of these special safety cars might well use these same techniques.

ESTIMATION OF COSTS AND PERSONNEL REQUIREMENTS FOR LONG-RANGE PLANNING

Several interesting problems have arisen in cost and personnel estimation because of the character of the NASA task. First, most work is conducted on a program or project basis instead of a continual process basis, and costs and personnel requirements are highly variable, if not discontinuous, as a function of time. Second, because of environmental factors such as the availability of funding, one can never be certain when and if a particular project will begin. Finally, the objectives and character of each project are entirely new; often the only relevant data for cost estimates must be gleaned from a few distantly related predecessors. Because space projects are constantly pressing against the state of the art, the estimation of costs and personnel requirements becomes a formidable task.

To meet problems, new and reasonably sophisticated models for estimating costs and personnel requirements have been needed. Two of these models will be described briefly here.

Probabilistic Long-Range Planning

With the aid of NASA funding, a number of related studies in the area of long-range probabilistic planning were undertaken at Texas A&M University. Long-range probabilistic planning is a general class of mathematical techniques used to facilitate the estimation of cost and personnel requirements. The mathematics of linear algebra and statistical analysis are combined into an overall systematic framework for dealing with managerial problems. An adaptation of these techniques should be applicable to those parts of both the public and private sector which operate on a program or project basis. Reference 1 lists and describes the series of related studies which have been completed in this area. This work has not been consolidated into a unified model as yet, and it will be necessary to extract the useful concepts from the separate reports. These reports are available from the NASA documentation system.

A Brief Description of the Methodology

The methodology developed by Texas A&M University can be used in the following type of situation: Consider an organization which is currently conducting a number of projects and will be conducting other projects in the future. How can such a firm predict its future manpower and resource requirements? The essence of this problem is that a firm cannot always be certain that it will receive a contract, nor can it be certain when it will receive such a contract. These two elements of uncertainty are inherent in such a situation, and the methods devised in this study can be used as a planning tool for these probabilistic situations.

The models use a combination of matrix techniques and standard statistical analysis. The basis is a forecasted manpower matrix. This matrix can be constructed when the firm divides the duration of the proposed contract into a number of equal time periods and decides what types of employees and how many of each will be needed during each period. In general, the forecasted manpower matrix has rows, each corresponding to a time period, and columns, each corresponding to a type of employee.

Once the matrix has been constructed, a manpower acquisition matrix can be generated by subtracting the $(j-l)^{\text{th}}$ row from the j^{th} row of the forecasted manpower matrix. This new matrix can be further divided into two matrices, one dealing with manpower acquisition from within the firm, and the other from outside.

The same type of analysis can be applied to budgetary estimation. One type of calculation that can be handled in this way is acquisition costs, obtained by forming a matrix in which rows represent the different types of personnel and columns represent the different types of costs associated with hiring new personnel, and multiplying this hiring cost matrix by the appropriate manpower matrix. Similar calculations can be performed for determining maintenance costs, production costs, etc.

Thus far, the probabilistic aspect of the problem has been neglected. The study uses two statistical concepts in an attempt to cope with this aspect:

(1) Application of subjective probabilities concerning the possibility of acquiring proposed projects

(2) Application of probability distributions for determination of the starting period of the proposed projects

The subjective probabilities for acquiring proposed projects may be obtained by considering the opinions of various key individuals in the firm and averaging their opinions to obtain a probability.

The study discusses three methods for estimating the starting date of a project. The first method, called the single best estimate, may be used when there is insufficient data from past experience with similar projects to form a probability distribution of the starting date. In this case, a single deterministic starting date is postulated. The second method may also be used where there is insufficient data from other projects. In the second method the starting date is a subjective probability distribution estimated by management personnel.

When sufficient historical data are available, a probability distribution of the starting date can be formed. The time periods used in forecasting the starting date are the same as those used in establishing the manpower requirements. In some instances, the volume of historical data may allow the probability of acquiring a project to be considered as a family of distribution functions, each of which is applicable during a given time period.

Having determined the subjective probabilities and derived the appropriate estimation of the starting date, these findings can be used to alter the entries in the forecasted manpower matrix and the other matrices derived from it. The new manpower matrices account for the nondeterministic aspect of long-range planning.

By using this system for each of the ongoing and proposed projects, management can construct a set of master manpower matrices for determining the quantity of each type of worker who should be hired or released during each time period. The costs of these personnel changes may also be calculated. By standard statistical techniques, management can compute means, variances, standard deviations, etc., of the number of employees required and the costs associated with them.

Potential Applications

The methodology developed in this study can be useful for businesses, government agencies, or any organization responsible for the operation and coordination of a number of discrete projects. An organization that is engaged in a large number of similar size projects and whose potential projects are of approximately the same size may find the techniques particularly useful. This characteristic is important, because the models developed in the study are often based on expected value calculations. Thus the models do not always allow for hedging against uncertainty.

The usefulness of the methodology can be increased if it can be applied to situations in which the time between the construction of the manpower matrix and the expected starting date of the project can be minimized. This is desirable because the accuracy of management's manpower estimates decreases as the time between planning and expected implementation increases. Technological change during the intervening time could alter both the types and number of employees needed for the project.

An example of an area where these techniques could be utilized would be an urban renewal program. The program might be divided into a number of projects such as the acquisition of land rights, razing of slums, and construction of new housing. For each of these projects manpower estimates could be made. The agency in charge of urban renewal activities would also estimate the probability that a specific project would be undertaken and develop a starting-date distribution. These data could then be combined into an overall long-range planning system for the urban renewal project.

The Manned Spacecraft Cost Model

To aid the NASA Manned Spacecraft Center in evaluating competing program missions and system designs, General Dynamics developed a comprehensive manned spacecraft cost model which—

(1) Generates cost estimates of the total program or any of its parts

(2) Predicts the Manned Spacecraft Center's personnel and resource requirements

(3) Estimates how expenditures vary with time

(4) Generates certain measures of cost effectiveness.

This cost model incorporates very general principles of cost estimation and applies them to the specific job of estimating costs for a manned space mission. The complete study is described in detail in reference 6.

The Problems for Which the Cost Model Was Developed

The Manned Spacecraft Center must choose between competing mission goals and the technological methods of accomplishing them. It must not only decide which programs are feasible, but also which are the least expensive for a given level of benefits. Scheduling missions and combining goals within certain missions reduces the cost of a program by making use of common research and facilities. Yet finding the best combination is difficult. A frequently used device or subsystem may influence total system cost significantly. Designers must decide when further research toward improving the device is worthwhile. All these factors combine to make cost estimation a formidable task for the management of a space program. The manned spacecraft cost model was designed as a possible approach to these problems.

A Description of the Cost Model

By modeling the characteristics of a real world system, designers can simulate and compare the effects of alternative decisions. The advantages of using one complete cost-estimating system are that it will—

(1) Take account of all significant cost factors

(2) Use a consistent set of values for variables in all calculations

(3) Use a uniform set of procedures in every costing problem.

The General Dynamics manned spacecraft cost model is a computerized procedure for analyzing the basic costs incurred in developing and operating a spacecraft system.

The model is composed of independent submodels. The decisionmaker may thus get an overview of the system and yet be able to study any section in depth. Subsystems may be modified or updated without reprograming the entire model. This feature allows parallel development and independent testing of the various program functions.

The model generates total costs by using information stored in a Cost Estimating Relationship (CER) library. A CER is the relationship between cost and various system parameters. CER's may be derived from data of past spacecraft programs. If sufficient data are available, multivariate regression analysis of the data can provide the "best-fit" cost relationship. If a subsystem is produced more than once, a learning curve submodel can adjust the associated CER's for decreasing costs to scale.

The model generates the program costs in a variety of ways. Total costs are broken down into increasingly smaller cost units from those of the entire space program to the spacecrafts, modules, and subsystems. The information is stored on tape and is available in any desired degree of detail. These total costs may also be used to estimate the time dependency of funding requirements.

The funding submodel predicts the spreading of an operation's absolute cost over time. The programer supplies the model with the starting and finishing times of an activity or the time at which a certain percentage of the activity is to be completed. The spreading of expenditures for similar previous operations determines the shaping parameters of a funding distribution function. Using the time "milestones" and the predetermined shaping parameters, the model estimates the required expenditures (adjusted for inflation, if desired) at fixed time intervals. The Center planning model performs similar operations to generate Manned Spacecraft Center personnel requirements.

To supplement the cost data, the model computes a measure of effectiveness per unit cost. Unfortunately, it is not easy to establish criteria of effectiveness because social, political, and scientific "profits" are difficult to quantify. Planners often use less satisfying, but more easily computable, criteria such as the probability of mission success. Cost effectiveness computations at this level of sophistication can provide crude guidelines for the decisionmaker.

The contingency planning model assesses the effects of unforeseen occurrences upon original cost estimates. There are eight contingencies whose impact the long-range planner may wish to analyze:

(1) Technological stretchout—delays in the programs schedule due to technological difficulties

(2) Budget constraint—an annual ceiling placed upon some part of a program budget

(3) Cost sharing—common usage of some subsystems and facilities

(4) Cancellation—cancellation of part or all of a program in terms of lost effort

(5) Technological recovery—substitution of one system by another with different technological complexities

(6) Acceleration—compressions of a previously defined schedule

(7) Parallel systems—development of two systems to perform the same function with the understanding that one will eventually be canceled in favor of the other

(8) Fixed costs—consideration given to incremental cost required to achieve additional operational capability

Knowing the consequences of possible contingencies and their likelihood enables decisionmakers to determine policy in accord with their expected preferences.

Systematic analysis and modeling of the costs of a complex organization is by no means confined to aerospace applications. Earlier sections of this survey report contain several examples of cost model applications to industry and urban problems.

MANAGEMENT INFORMATION AND CONTROL TECHNIQUES

Man's first steps into space have necessarily been giant steps, characterized by large and complex systems. Management control and information systems have been needed to monitor and evaluate the results of the vast multivarious activities which are combined into typical space systems. Recognizing the individual requirements of their respective projects, the management teams of each of the NASA projects have devised interlocking networks of management control and information systems. Several new management control techniques, developed in conjunction with NASA projects, will be described here as examples of techniques which may be transferred to nonaerospace fields.

It is difficult to delineate the boundaries and scope of management control and information systems because these systems are inextricably involved in the process of management as a total function. For our purposes, it will suffice to describe an information and control system as a systematic set of techniques and information flows, the goal of which is the monitoring, evaluation, and control of the status of an overall program. The systems attain these goals by combining a set of elements, among which are: internal flows of documents and data; flows of external environmental data; systematic procedures to digest, extract, and analyze the data; evaluation of the data with respect to the program objectives;

and a feedback control mechanism which provides for initiation of action on the basis of the data. Obviously these same tasks are essential activities in any large, complex undertaking.

Although the management systems for large and complex undertakings fulfill certain general and common objectives, there are no general criteria or rules of thumb that describe their structures. Effective management control and information systems must clearly be individually tailored to meet the specific requirements of a program. It is obvious that a complete management system cannot be lifted from a space program and applied effectively in another endeavor. To search for such direct and complete transferability would be to misunderstand the process of designing and implementing effective management systems. Rather, one must concentrate on the techniques that have been developed as individual elements in control and information systems. These techniques are the real contributions of NASA projects to control and information systems, and in them lies the promise of transfer to industrial and urban programs. This section will describe first an information and control system developed during the Apollo program to monitor, evaluate, and predict key indices of the Apollo system. Second, a systematic procedure which generates the performance indices by which a complex multiobjective program may be evaluated will be described.

FAME—An Information and Control System Developed for the Apollo Program

The Apollo program office system, referred to as Forecasts and Appraisals for Management Evaluation (FAME), is documented in detail in reference 7. In the following paragraphs, a more concise description of the system will be presented.

The Management Problems for Which FAME Was Developed

The Apollo project is a vast collection of interrelated activities, the goal of which is to develop a launch vehicle and spacecraft system to land men on the lunar surface. The total system must attain this goal while operating within certain constraints and performance tolerances. In particular, the weight of the total system is constrained in fairly severe ways by the capability of the launch vehicle. The design, development, and production of all subsystems must therefore be carefully controlled within the tolerances established by the initial weight budget. The weight control problems are further magnified by the large number of individual contractors who manufacture separate units, each of which has an effect on the cumulative weight totals. Weight estimates have to be ascertained early in the design and development stage, and then accumulated and passed upward through the component, assembly, subsystem, and system levels. The Apollo program office thus needed—

(1) An information system to generate, update, and transmit crucial weight data at regular time intervals

(2) A systematic method of recording and analyzing these data

(3) A systematic way of appraising the criticality of any departures from expected weight tolerances

(4) Most important, a method of projecting observed weight trends into the future

The FAME system, developed in response to these needs, is a novel application of data-handling and statistical techniques to this type of management problem.

A Detailed Description of the FAME System

To accomplish adequately the weight control tasks, a complete system of data handling and analysis is required. For each subsystem or component in the Apollo program, historical weight data must be collected, recorded, and analyzed, and forecasts of future weight trends must be made. The results of this analysis and forecast must then be evaluated and forwarded to cognizant management levels. This is accomplished in FAME by the combination of several information and control techniques.

The FAME system begins with an information system designed to ensure the upward flow of accurate weight estimates from the myriad contractors to the program office. These raw historical data are then preprocessed by removing all nonrandom fluctuations caused by design changes.

Also, a careful study of the mission requirements and constraints is pursued, yielding a set of control limits for the weight of each component or subsystem. Armed with these two sets of input, the preprocessed historical data and the appropriate control limits for these data, FAME is ready to proceed with the analysis of historical trends and the forecast which projects trends into the future.

The forecast analysis is accomplished by using not one, but four different mathematical models, each of which has its own advantages and drawbacks as a predictive tool. The four underlying statistical techniques may be described as follows:

(1) A linear maximum-likelihood method
(2) A nonlinear maximum-likelihood method
(3) An asymptotic (logistic) exponential method
(4) An adaptive (Fourier) exponential method

Each one will ascertain different "trends" in the data and furnish different forecasts of future developments. The choice of trend model is a crucial decision in the system operation and is by no means a trivial step. In FAME this choice can be made manually or automatically, depending on the user's requirements. The automatic mode provides a fairly sophisticated range of methods which test the validity of each mathematical model for predicting weight trends in a given subsystem. On the basis of these criteria, one model which generates the best trends for the problem at hand is chosen by the decision module. Finally, the forecasts produced by the model are adjusted for biases, expected program changes, and factors related to the program maturity (stage in design, development, production, etc.). (These adjustments are described in detail in the references already mentioned.) The probable errors in the forecasts are then computed as the final stage in the statistical treatment of the data. The output of this stage of FAME is, then, a set of historical trends, forecasted weights, and the probable errors in these forecasts for each relevant unit of the total spacecraft system.

To help management evaluate the data and forecasts which are generated, FAME performs a number of ancillary calculations. All of the trends are accumulated and summed to present a consistent picture of the total weight of the system. Each individual weight excess or predicted weight excess is then examined to ascertain the criticality of the problems involved. The degree of criticality for any particular unit is determined by an analysis of the trade-offs and performance adjustments that will be required. The criticality rankings performed by the FAME program are a great aid in calling management's attention to the most immediate problems. The final element of the FAME system is the output and set of management reports necessary to transmit the historical data and forecasts to the proper decisionmakers. FAME provides for the transmission of the following information, either in the form of data or in graphical displays:

(1) Current status of the program and its elements
(2) Predicted status of the program and its elements
(3) Problem areas
(4) Criticality of the problem areas
(5) Trade-offs necessary to correct the problem area

With this final element, the FAME program is a completed set of techniques for the purposes of management information and control. In brief review, it consists of the following important elements:

(1) An information gathering system
(2) A preprocessing technique for the data
(3) A set of statistical techniques to assess historical trends and generate forecasts
(4) A set of criteria to evaluate the data and forecasts in terms of their criticality to the program as a whole
(5) An output and reporting system for transmission of the final appraisals.

Assuming proper action by the program management, the FAME system provides a closed-loop system of information and control for monitoring, predicting, evaluating, and finally controlling the weight of the Apollo spacecraft program. It provides for timely recognition of weight control problems and the determination of their overall effect so that disturbances can be minimized.

Potential Applications of the FAME System

As pointed out in reference 7, the FAME system is by no means confined to weight control problems. It can be easily adapted to the monitoring of other important program parameters in the Apollo program; for example, cost control, scheduling, reliability control, and performance assessment. Although these adaptations have not as yet been accomplished, their general formats are outlined briefly in the final section of the referenced document.

Both the general format of the FAME system and the techniques used in its various elements hold great promise for application in many fields of endeavor. The statistical techniques used in FAME's forecast analysis are reasonably sophisticated, although well known. More importantly, they have been packaged into an overall module in an innovative and unique way so that the results are well suited for presentation to a decision-maker. Any statistical problem which demands the determination of trends in historical data and projection of these trends into the future may be efficiently attacked by the use of techniques included in this system.

Consumer-oriented industries may well wish to consider the utilization of systems similar to FAME to enhance their market research and sales forecasting efforts. Historical data in time-series form may be generated to describe the marketplace in terms of total primary demand, market share for a particular product, dollar sales for a particular product, etc. Any of these data may then be analyzed periodically by a FAME system. Many industrial enterprises already use certain statistical techniques for sales forecasting, but rarely are these forecasting efforts embedded in as complete a management control and information system as FAME.

An even larger potential use of FAME arises in the area of cost control for industrial enterprises. Effective cost control in any large industrial complex demands rather cumbersome budgetary techniques, periodic surveillance of actual cost data, and comparison of the actual cost data with the budgeted limits. A system similar to FAME could be utilized to automate these functions and to present the results to management in a form most convenient for decisionmaking. The system would also generate cost forecasts on the basis of historical trends, a task which could prove very helpful in identifying possible problem areas. Furthermore, the module of FAME which automatically ascertains the criticality of budgetary excesses is a feature usually absent in even the most advanced cost control programs now in industrial use.

Another potential use of this type of information and control system is in the area of quality assurance for large manufacturing complexes. Wherever quality control data can be generated on a regular periodic basis, a system similar to FAME can be utilized to monitor, evaluate, and report on the results of a quality control program.

Finally, a system like FAME could be used in large decentralized enterprises to assess, analyze, and forecast profits automatically for all the operating units as the corporation's fiscal year progresses. This system could be used as a step away from the concept of totally decentralized operating units, or alternatively, it could be used solely as an information system designed to keep top management abreast of recent and projected developments with little or no feedback into a centralized control system.

A system like FAME is flexible and general enough to accommodate the analysis and projection of many different types of data. Because of this advantage, a large industrial corporation could utilize a program patterned after FAME to perform not one, but all of the tasks just described. In effect, the sales forecasting, cost control, quality control, and profit monitoring functions could be combined into an integrated management information and control system with common information channels and reporting mechanisms. Few such complete information and control systems are currently in industrial use.

Public programs, particularly in large urban areas, also require fairly sophisticated information and control techniques in order to operate effectively. Many historical time-series of data are used in urban planning, and the techniques of FAME can be used to analyze, evaluate, and predict program needs on the basis of these data. In addition, the daily operating functions of the various urban authorities might well utilize a FAME system to evaluate parameters related to their spheres of responsibility. The FAME system would also be useful in other areas:

(1) In public health—to aid in the monitoring and evaluation of current data on illnesses, particularly communicable diseases

(2) In air pollution control—to monitor the level of pollutants in the air in various localities

(3) In city administration—to increase the effectiveness of budgetary control procedures

Mission Success Evaluation—A Technique for Deriving and Utilizing Measures of Performance

The typical space program is a complex set of missions and spacecraft. The myriad subsystems involved in any one spacecraft are related in fairly complex ways to the particular flight objectives of that spacecraft, and the specific set of flight objectives is altered as the space program evolves from one spacecraft to the next. Against this background of conflicting, evolving objectives attained by complex systems of interrelated subsystems, the program management must make long-range planning decisions, as well as periodic management control decisions. To approach systematically the management problems of such a program, it is both desirable and necessary to reduce the complex operations of the multiobjective program to several key performance indices. These measures of performance can then be used to monitor, evaluate, and control the program, and furthermore can be used as the basis for trade-off studies of the optimal allocation of available resources. A particularly systematic and concise method for devising and utilizing such a measure of performance is described in reference 8. These methods were devised for the evaluation of the Surveyor program at the Jet Propulsion Laboratory, but the techniques hold promise for application to any complex multiobjective program.

A Brief Description of the Techniques

As the first step in the derivation and use of performance indices, the vast array of objectives is classified and codified into a hierarchy of interrelated objectives. This hierarchy consists of several different levels of objectives, ranging from the philosophically worded general goals of the program, to the specific detailed events that must be accomplished by any one spacecraft during its flight. Second, the importance of various flight objectives to the success of the mission as a whole is ascertained. Each flight objective is assigned a weighting factor which is a quantitative measure of its relative importance in the hierarchy of objectives. Several methods for deriving these weighting factors are discussed in some detail in the referenced document. The flight objectives and their weighting factors are then combined into both *a priori* and *a posteriori* performance indices for a space flight. A measure of performance, the *a posteriori* index, is defined as a particular combination of weighting factors which reflects the relative importance of the flight objectives actually accomplished by a given flight. Similarly, a probable measure of performance is defined as a weighted average of individual success probabilities which reflects the relative importance of the anticipated objectives for a future flight.

With these performance indices, mathematical models are constructed which describe the probability of different degrees of mission success. The objectives and subsystems necessary for their attainment are arrayed in a matrix format to illustrate the system interdependencies. A Markovian approach is utilized to illustrate the evolution of individual success probabilities from one spacecraft mission to the next. These tools are then combined into an overall framework for evaluating the successful performance of the entire space project.

The Application of These Techniques to Nonaerospace Endeavors

The techniques briefly described above, and described in full detail in the referenced report, are clearly applicable to any complex multiobjective program. They involve no abstruse mathematics or principles, but rather comprise a systematic attempt to derive criteria upon which complex programs may be evaluated. These techniques illustrate the application of the systems approach to large-scale planning and control problems. They may be useful additions to the management information and control systems in many nonaerospace activities.

There is a particularly acute need for this type of methodology in large multiobjective urban programs where the results are difficult to quantify in terms of one performance index. As an example, consider an urban redevelopment program in a large urban area. The objectives of such a program are a multitude of economic and social goals, related to each other in what the above reference describes as a hierarchy of objectives. Furthermore, the program will evolve through several stages, each one of which has a separate but not mutually exclusive set of goals (much as in a large space program with several flights). The proper planning, monitoring, and evaluation of such a large program will require a systematic set of management information and controls. As part of this system, the above techniques can be put to excellent use.

OTHER MATHEMATICAL MODELS AND MANAGEMENT TECHNIQUES

This section of the survey report describes three important models developed with NASA funding, which do not fall neatly into any of the previously discussed general categories. They are included here with a few brief comments on their application to nonaerospace endeavors.

GREMEX—A Game to Provide Experience in R&D Project Management

The Goddard Space Flight Center developed the GREMEX (Goddard Research Engineering Management Exercise) simulation to provide experience in R&D decisionmaking for personnel involved in aerospace project management. A fairly complete description of this gaming simulation is available in reference 9. The need for this simulation arose from two of the basic characteristics of the aerospace industry: the relative newness of the field and the relative shortage of engineers and scientists with management experience.

A Detailed Description of GREMEX

GREMEX is a man-machine interaction in which the decisions of the participants are translated into a computer language and fed into a computer which stores a mathematical model that evaluates the decisions. The simulation is divided into a number of periods, each of which corresponds to 1 month in real time. During each of the periods, the participants receive information regarding the outcome of the decisions which they reached during the previous period. The participants use this information as a basis for reaching new decisions or revising their earlier decisions.

Each of the participants in GREMEX plays the role of a manager of an Orbiting Optical Observatory Project, the overall objective of which is to launch a spacecraft beyond the earth's atmosphere and magnetic field to conduct experiments in solar physics. A number of different experiments can be conducted, and part of the exercise is to determine which experiments should be attempted.

As presently conducted, participants are then combined into teams of three players. Each team has a set of time, cost, and performance objectives for the project. Their decisions help to determine the degree to which these objectives are met. A computer, programed with a mathematical model, uses these decisions to calculate time, cost, and performance estimates. The computer also generates a set of random occurrences to simulate the uncertainties inherent in the management of an R&D project.

The exercise begins with an indoctrination period, at which time the players review a Player Manual, which contains information that describes the simulated project and presents evaluations of five potential contractors for the project. Also included are funding and manpower resources, milestone schedules, and PERT charts.

Using the information, the players enter the first decision period, during which they are required to let the project to one of the five alternative contractors and decide which of the experiments should be included in the final project launching. Decisions are also reached regarding reporting requirements and starting dates. All these decisions are fed into the computer, which then calculates inherent success probabilities for achieving the time, cost, and performance objectives. The computer also prints out a series of reports which may be requested by players during the subsequent period and advances the time frame 1 month.

Each player then has the opportunity to request the reports, which form his management information system and which he can use to assess the results of the previous month's decisions. Based upon this information, the player can make new decisions or modify old ones. He is also required to prepare a status report on the project for use during the postgame debriefing. At the end of each period, the computer is fed any new decisions and repeats the cycle.

At the conclusion of the game a debriefing period is conducted by the instructor-referee, who functioned as buffer between the players and the computer while the exercise was in progress. The instructor-referee checks the legality of the players' actions, provides the players with the information they requested and the chance occurrences generated by the computer, and acts in several role-playing capacities as well as conducting debriefings.

Potential Applications of GREMEX

The management of research and development is a problem that is by no means limited to the aerospace industry. Although the complete content of GREMEX would not be transferable to activities outside the aerospace industry, the techniques used in the simulation may be transferred. These techniques involve the following:

(1) The definition of an overall objective

(2) Designing a mathematical model that can be utilized by a computer

(3) The assignment of players to roles and the provision of certain types of information to these players

(4) Developing a set of rules to govern decisionmaking

(5) Designing an appropriate set of indices to measure the players' performance

(6) Determining an appropriate move sequence

Many large industries allocate part of their budget to research and development. A simulation such as GREMEX would provide valuable experience for the industry's R&D personnel. The feasibility of a simulation would be governed, to a large degree, by the designer's ability to construct an appropriate mathematical model and performance criteria. These can usually be developed if a suitably small set of parameters can be used to construct meaningful performance criteria. The number of parameters necessary for the construction of a realistic model can be determined only after a study of the specific situation that is to be simulated.

In those situations where the number of parameters is quite limited, a GREMEX-type simulation would be a suitable addition to an industry's management training program.

Simulations can be utilized by any organization or agency which engages in research and development activities. One example would be a government agency responsible for the operation of an urban renewal program. This agency would have to let contracts for the razing of slums and the construction of new homes. It would have an overall objective, which might be the provision of new low-cost housing for 500 families. Chance occurrences, e.g., a riot, might impose some unexpected conditions and requirements on the agency. A simulation of the urban renewal problem could, therefore, use many of the techniques utilized by GREMEX.

Regardless of where it is applied, the technique of simulation allows participants to recognize the problems inherent in the managing of a large-scale project and to see the consequences of their decisions. Because simulations have these capabilities, they are a useful tool for the training of management personnel.

Urban Employment Multipliers and Their Application to the Aerospace Industry

A model of the effects of new employment on urban environment is described in detail in reference 10. The purpose of the work was to investigate the relationship between employment changes in several key aerospace industries in St. Louis and employment in the St. Louis economy as a whole.

The concept of one new job creating others is called a multiplier in economic theory, and effects of employment multipliers have been discussed and studied for some time. This study, however, was a pioneering one in several respects. First, it used seasonal corrections and time-series analysis to remove factors which were not the subject of the study, with the result that the final equation developed showed the very high correlation coefficient of 0.96 (i.e., the model explained almost all the fluctuations in employment in the St. Louis area). Second, the study used a timelag between changes in the exporting industry and its effect on the rest of the area's economy. It was found that a 3-month timelag gave the best fit.

The most important innovation of the study, however, was that it differentiated between the impact of employment expansion in the different exporting industries. An important conclusion was that the effects differed widely from one industry to another. For example, every

10 000 jobs created by a DOD or NASA contract in the aerospace industry produced, after a lag of 3 months, 8256 other jobs in the St. Louis area. In the electrical machinery industries, however, each 10 000 jobs would create 27 112 others, a substantially higher multiplier. These differences are only partly dependent on the nature of these two industries. They depend much more on the structure of the local economy. The low multiplier for aerospace arose from the fact that a large aerospace company subcontracts much work and buys parts from other aerospace industry firms, many of which are not located in the St. Louis area. In southern California, where there is a great concentration of aerospace industry companies, we would expect the aerospace multiplier to be higher. The results of the study are, therefore, specific to the St. Louis region, though the same methodology could be applied elsewhere.

The potential uses of this study and its methodology lie in two areas, government—local, state, and federal—and business. Other government users of these data will be city planners who will need to know how employment and population will expand so that they can provide facilities accordingly. The study can also help local government to anticipate changes in the tax base and the needs for the services that it provides.

Suppose that an aerospace company were planning to build in St. Louis a facility which would eventually employ a labor force of a thousand. If the rate at which employment was to be expanded at the facility was known and the number of people to be employed in construction work and the period for which they were to be employed was also known, an analysis would tell government officials at both the state and city levels the following:

(1) How many new jobs would be created in the city as a result of the aerospace company moving in

(2) The timing of the creation of these new jobs. There would be a delay between the creation of a job at the aerospace company and the creation of the other jobs

(3) How many new jobs would be created as a result of the construction of the facility

(4) The timing of the expansion and construction of the jobs related to the construction work

In this way an overall picture of the impact of this company's decision would be forecasted, and decisions on highway construction, school system expansion, and other matters could be made accordingly.

Corporations can use the study to estimate the impact of their plans on the communities in which they operate, provided the necessary input data are available. If they plan to leave a certain location, they can estimate the magnitude of the impact of their decision. If they propose to open a plant in a new location, this study may help them estimate the overall effect of their action on the community. It might also help them avoid overestimating the supply of labor in the new location.

Contractor Decisionmaking and Incentive Fee Contracts

Reference 11 reports the results of a study of a mathematical model of the contractor decisionmaking process and how it affects the concept of incentive fee contracts. The mathematical model developed in this study is used to evaluate the incentive fee contract by invoking decision-theory techniques. The contractor is characterized by his utility function, and the elements of his decision under uncertainty are analyzed. More importantly, the implications of these decisions are explored for incentive fee contracts. The study concludes that it is extremely difficult to motivate contractors with large incentive fees. Contractors are more interested in future sales; and any contractual inducements might be more efficient if they were directed at these long-range interests.

The applications of this study to nonaerospace endeavors is self-evident, and this survey report will not belabor these obvious extensions. This study may be helpful to any private or governmental organization which originates many contractual relationships, particularly those currently using or considering incentive fee contracts.

CHAPTER V

Closing Remarks

This survey has described major problem areas in endeavors outside the aerospace industry and suggested systems techniques which may be helpful in approaching these problem areas. Emphasis has been placed upon techniques developed and applied with the aid of NASA funding. Because of the breadth of subject matter, there has been no comprehensive and rigorous discussion of any one technique or problem area. Readers interested in delving further into the potential uses of techniques described are urged to consult the reference source documents. These documents may be obtained through U.S. Government channels and are sometimes available at the originating source. Those organizations which are eligible to receive NASA documents without charge (including all U.S. Government agencies and their contractors) should consult the NASA Scientific and Technical Information Facility, College Park, Maryland.

It is clear that systems analysis techniques have potential for application to many nonaerospace activities. They provide a set of consistent and systematic models which deal with problems in their entirety. They provide a framework for addressing the meaningful decisions which must be made in many fields. Although these systems techniques are no panacea for the ills of an organization, they can facilitate the solution of management problems surrounding large complex endeavors in both the private and public sectors of the economy.

Glossary

decision tree—an illustrative device used to diagram the logical flow of a series of decisions. Various "branches" of the decision tree emanating from common points represent either alternative decisions or alternative external events which affect these decisions.

dynamic programing—a class of optimization techniques where a sequence of time-ordered events are optimized with respect to some criteria.

employment multiplier—the multiplier effect applied to the labor force in a specified region and/or industry (see **multiplier effect**).

game theory techniques—a general class of techniques which analyze and specify decision rules in situations where the outcomes or "payoffs" are determined by the action of two or more independent parties.

learning curve—a curve which in some particular context depicts the increased efficiency due to the repetitive performance of a function.

linear programing—a class of optimization techniques where a set of variables are chosen to optimize some criterion's function subject to some constraints. The variables must enter linearly into the constraints and the criterion function.

Markov chain—a type of time-ordered probabilistic process which passes from one well-defined state to another according to probabilistic transition rules which are determined by the current state.

matrix—a two-dimensional array of numbers organized spatially into rows and columns.

Monte Carlo techniques—a set of probabilistic simulation techniques where the distribution of final results is generated by the individual results of many separate trials, each trial corresponding to a set of randomly chosen input conditions.

multiplier effect—an economic phenomenon where the net final change in some criterion (e.g., number of jobs) is larger than the initial stimulus due to a multiplying or intensifying mechanism.

multivariate regression analysis—a statistical technique used to develop a relationship between one dependent variable and a set of independent variables by employing the multidimensional analog of "curve fitting" least-square techniques.

nonlinear programing—a class of optimization techniques where a set of variables are chosen to optimize some criterion function subject to some constraints. The variables do not enter linearly into the constraints and/or the criterion function.

numéraire—a variable which is used as a criterion to evaluate a decision, policy, action, and so forth.

profit center system—a decentralized form of corporate organizational structure where separate units are judged on the basis of their individual contribution to total corporate profit

statistical decision theory—a set of techniques used to analyze complex decision problems, combining subjective probability assessments and preference or utility functions.

subjective probability distribution—a probability distribution corresponding to judgments about the likelihood of future events rather than the objectively observed relative frequency of phenomena.

utility theory—a set of concepts used to order and express one's relative preference for objects and events.

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